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Seasonal characterization of the nutrients state in Oualidia Lagoon (Moroccan Atlantic coast)

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- ✓ Atlantic,
- ✓ Morocco

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Abstract

The nutrient cycle in Oualidia lagoon, on the Atlantic Moroccan coast, was studied at both spatial and temporal scales, covering spring and summer conditions. Water samples were collected bimonthly at high tide from March to August during years 2011 and 2012 at six stations distributed throughout the lagoon. The physico-chemistry (temperature, salinity, dissolved O_2) and nutrient enrichment of the lagoon surface water were monitored. The average nutrient concentration of surface water were 14.4 µmol.l^{-1} and 28.1 µmol.l^{-1} for NH_4^+, 20.4 µmol.l^{-1} and 19.9 µmol.l^{-1} for PO_4^{3-} and 3.7 µmol.l^{-1} and 7.6 µmol.l^{-1} for NO_2^- in 2011 and 2012, respectively. Strong seasonal differences of nutrient distribution at the different stations were noticed. Temperature, salinity and dissolved O_2 were correlated with nutrient concentrations, all parameters showing low spatial (inter-station) variability. Hydrological conditions exert a major control on the nutrient cycling in the lagoon. Results of this study are important to increase the richness on the scientific knowledge of nutrient dynamics along the Moroccan Atlantic coast, particularly in the semi-enclosed lagoons that are important transitional systems.

1. Introduction

Coastal lagoons constitute ecosystems of ecologic, economic and social value [1] . High biological productivity is a common characteristic they share [2] due to the coupling of several processes which include: (1) elevated inputs of nutrients due to land runoff; (2) shallowness, allowing light penetration in the whole water column and high exchanges of chemical variables (nutrients, oxygen etc) between sediments and the water column; and (3) partial isolation from the sea[3]. Factors affecting the nutrient cycling in coastal lagoons on a temporal scale have been extensively characterized for a number of different systems [4, 5], showing that nutrient regeneration in the water column and sediments is a key factor enhancing phytoplankton production [6, 7]. These studies generally rely on data obtained from surface water sampling at high tide.

Lagoons are highly dynamic environments, subject to frequent fluctuations under control of physical processes[8, 9] and especially sensitive to natural disturbances [1, 10]. In the context of the global change, the vulnerability of these systems is even greater and the sea-level rise, storm intensification, tidal regime alterations or freshwater input changes can significantly impact the functioning of coastal lagoons [11]. But these systems are further facing serious problems due to anthropogenic activities, such as intense agricultural, fishing and tourism activities, changes in land use, destruction of mangroves, aquaculture effluents, overfishing, use of illegal fishing techniques (i.e., dynamite and cyanide), sedimentation, waste discharge and fertilizer and pesticide use[12].

Studying the spatio-temporal dynamics of nutrients in lagoons is necessary in the context of climate change and increasing human disturbances on these systems[13]. Thus, the aim of this work was to study a Moroccan lagoon representative of the Atlantic coast in order to (i) delineate a quantitative and qualitative physico-chemical description of its surface waters; (ii) to assess the spatio-temporal dynamic of nutrients of its surface waters; (iii) to highlight relationships between nutrient dynamics and the physico-chemical forcing parameters monitored.

2. Materials and methods

2.1. *Study site*

The Oualidia lagoon (32°46'N, 09°01'W; Fig. 1) is located on the Moroccan Atlantic coast between the cities of El Jadida and Safi. It is about 7 km long and 0.5 km wide, covers an area of 4 km^2 and has a mean depth of 1.5 m. Water is exchanged with the sea by two inlets: a main pass (150 m wide), permanent and active throughout the year, and a secondary one (50 m wide). The lagoon is subdivided in several parts that are connected by a main channel with a maximum depth not exceeding 5 to 6 m and a secondary channel with a maximum depth of 1.0 to 1.5 m. The lagoon is separated from the salt marshes by an artificial dike in the north.

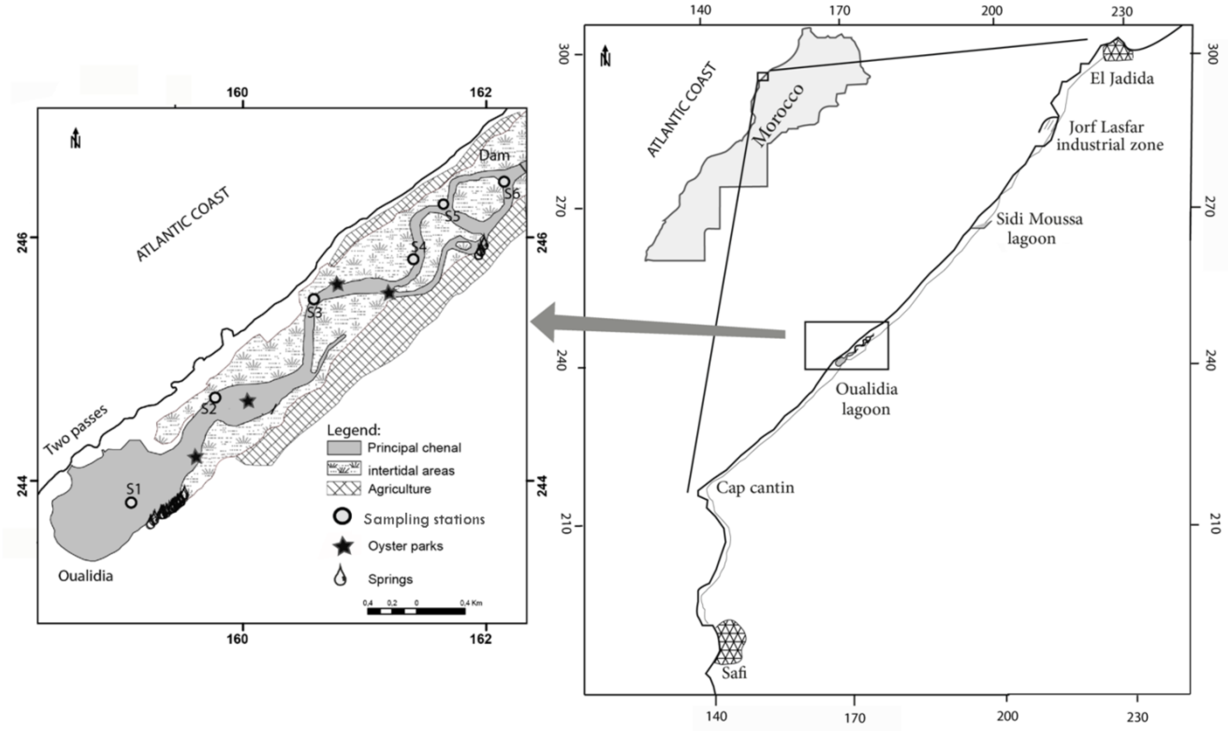


Figure 1: General map of the Atlantic northwestern coast of Morocco (right) and zoom on the Oualidia lagoon (left). The position of the six sampling stations S1 to S6 is shown in the lagoon map.

2.2. *Sampling and analytical methods*

Twenty-four sampling surveys were carried out during spring and summer periods of years 2011 and 2012, at high tide. Water samples were collected from the first 10 cm surface water for nutrient analysis and physico-chemical parameters were measured *in situ* concomitantly to that sampling. Six stations distributed in the lagoon from the downstream sea-side (S1) to the upstream land-side (S6) were studied in order to determine the spatio-temporal variability along that gradient as well as the influence of several human activities (oyster culture, agriculture; Fig. 1). The physico-chemical parameters: temperature, dissolved O_2 and salinity were measured using a calibrated multiparametric probe Multi340i (wtw82362 Weilheim). For nutrients analysis, water samples were collected in triplicate by using 1 liter HD-PE plastic bottles. Water samples were stored at 4°C, brought to the laboratory and rapidly analyzed within 48 hrs. Water samples were filtered using a Millipore system with fiberglass Whatman GF/C filters of 47 mm diameter and 0.45µm porosity. Filtration is essential to eliminate any suspended matters that are susceptible to absorb light during the colorimetric analysis and to modify the chemical composition of the analyzed solution. Nutrient (ammonium, nitrite and orthophosphate) concentrations were determined by colorimetric approach using a spectrometer (BIOMATE 3) according to the standard method AFNOR (P: NF T 90-023, NO_2^-: NF T90-013and NH_4^+: NF T 90-015) [14]. Specifying the triplicate measurements were performed on each samples, for each nutrient.

2.3. *Mathematical and statistical analysis*

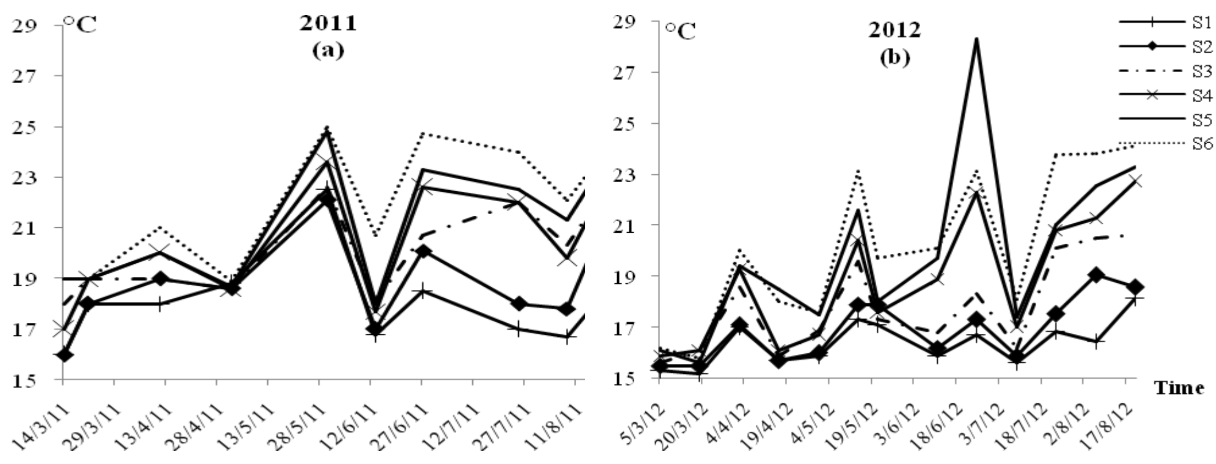
Data were processed in order to calculate seasonal and annuals means, maximum and minimum values. The annual means were used to account for the spatial variability of physico-chemical parameters and nutrient concentrations of the lagoon surface water. Results were visualized as contour maps created using ArcGis (version 9.x, Esri). Correlations between the monitored variables (temperature, salinity, dissolved O_2, PO_4^{3-}, NO_2^-, and NH_4^+) were assessed using the Spearman test. Principal Component Analysis (PCA) was performed on the correlation matrix of the 6 variables. Statistical analyzes were performed using SPSS (version 10 for Windows, SPSS, Chicago, IL, USA).

3. Results and discussion

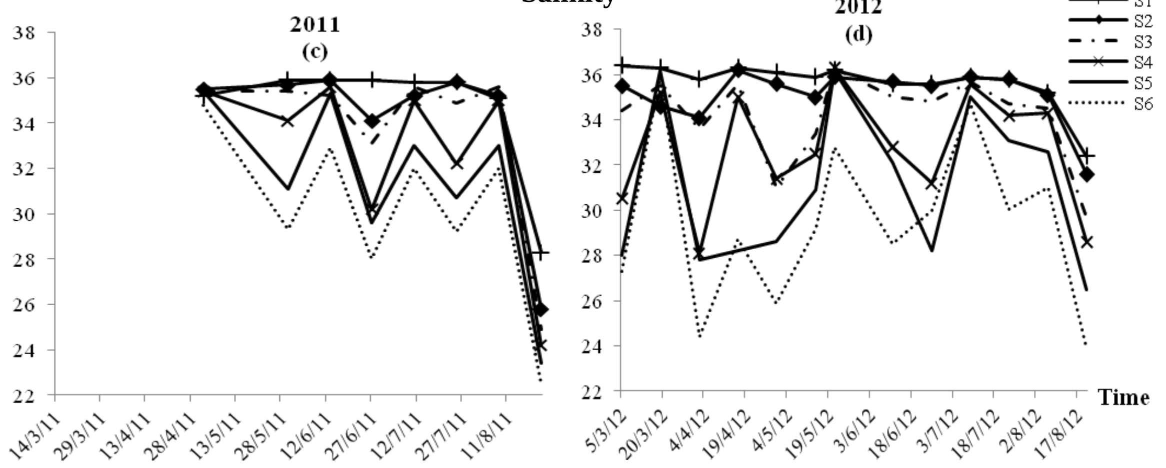
3.1. *Distribution of physico-chemical water quality parameters*

Distribution of surface water temperature in spring-summer 2011 in the Oualidia lagoon showed a minimum of 15.2°C for stations S1 and S2 (downstream) in spring and a maximum of 25°C for station S6 (upstream) in summer (Fig. 2a), with an average of 19.9°C (Table 1). In spring-summer 2012 the surface water temperature varied between a minimum of 15.2°C for station S1 (downstream) in spring and a maximum 24.1°C for station S6 (upstream) in summer (Fig. 2b), the average value being 18.4°C (Table 1). The surface water temperature in the Oualidia lagoon decreased from upstream to downstream (Figs. 3a, b) and was higher in 2011 compared to 2012 (except in summer in stations S5 and S6 (Table 1). The Oualidia lagoon water temperature ranges were relatively narrow (15.2 - 25.0°C) during spring-summer 2011 and 2012. That observation was consistent with previous studies on this lagoon [15, 16, 17, 18, 19, 20, 9] . Seasonal variability of temperature (Table 1) could be explained by the influence of ocean and atmospheric temperature (12°C in winter and 24°C in summer) [21] on the freshwater feeding the lagoon. The present study showed a gradual rise of temperature from spring to summer. That seasonal increase in temperature could explain the phytoplankton blooms observed in spring [16].

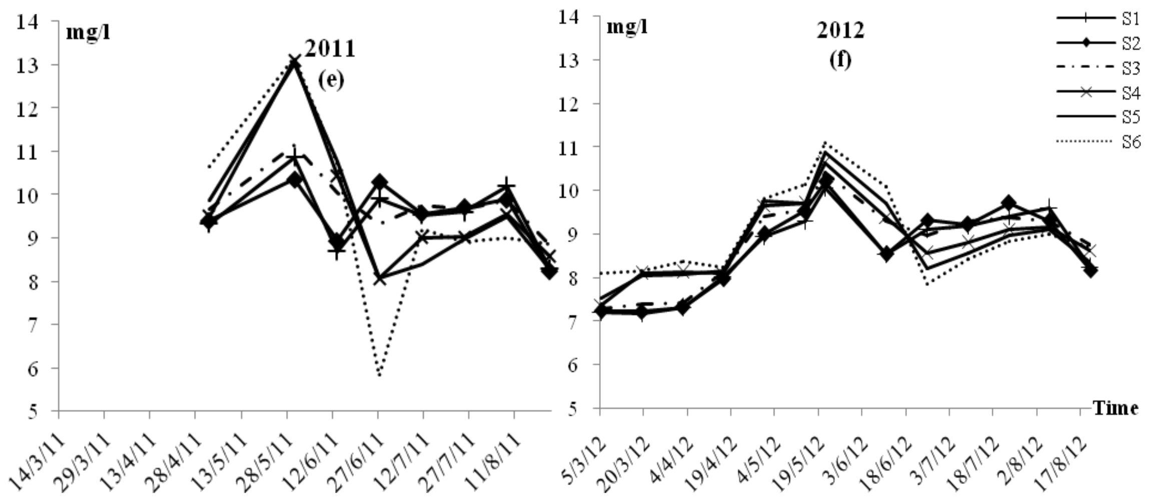
Temperature

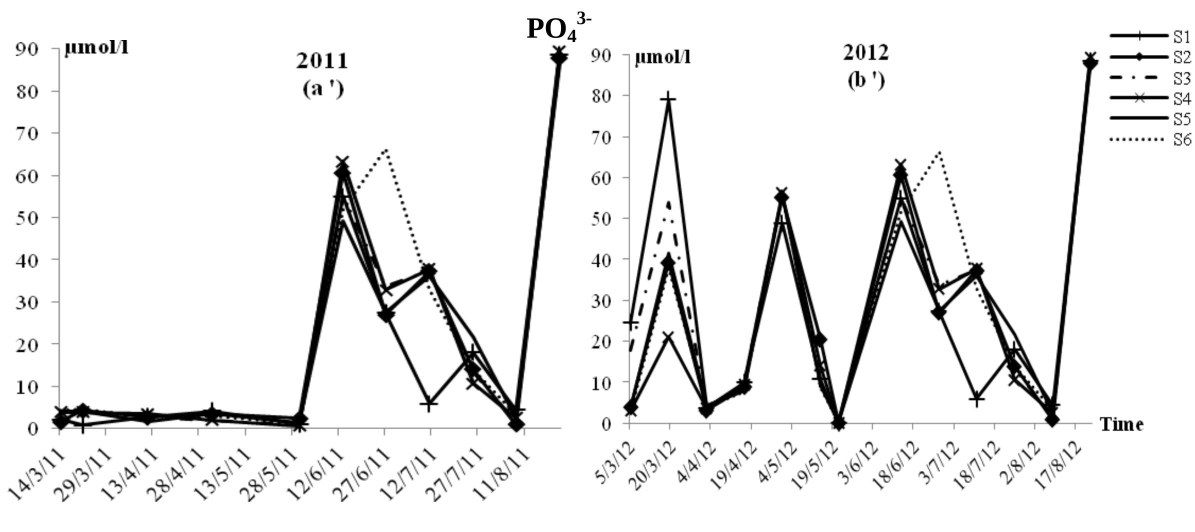


Salinity



Dissolved O_2





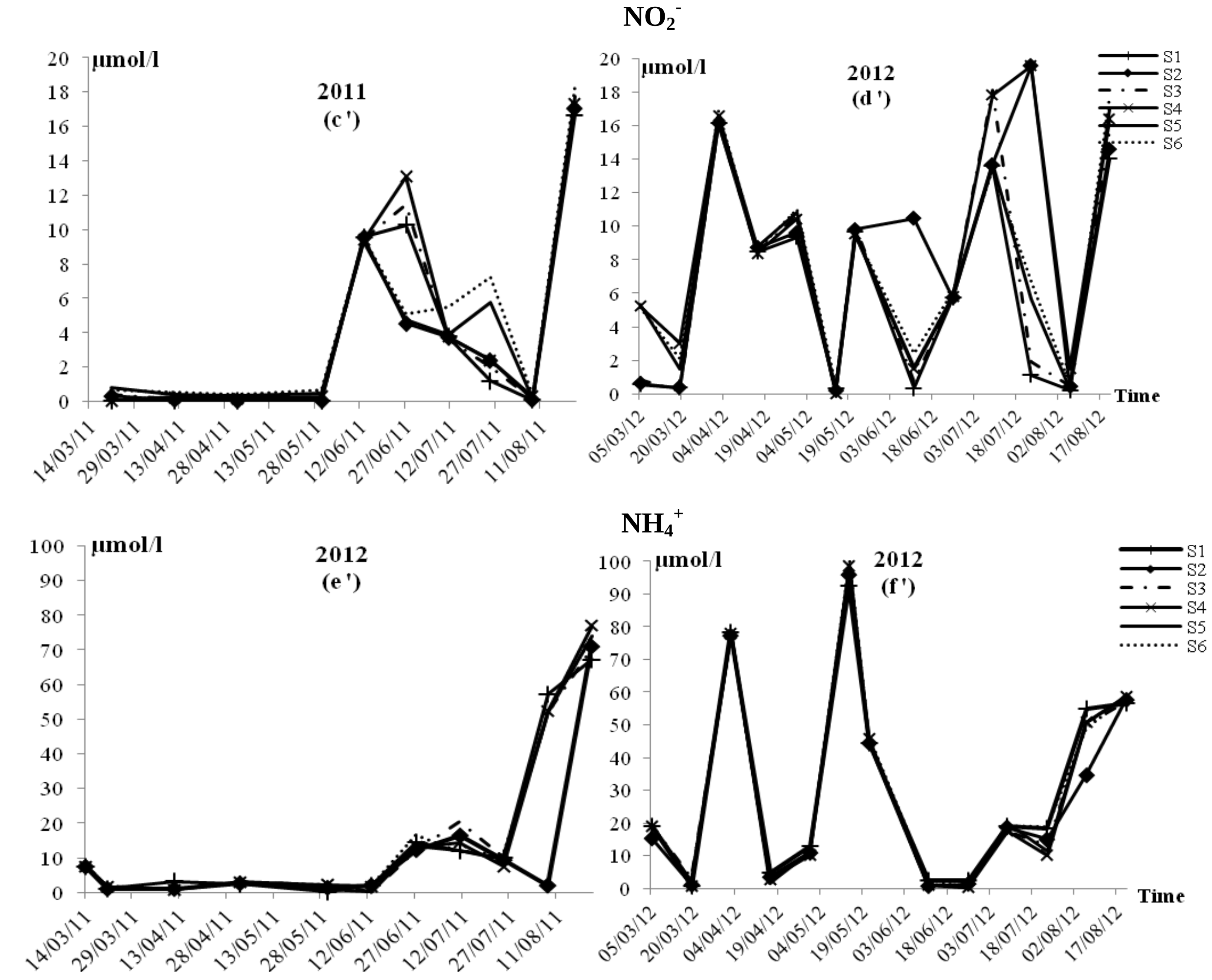


Figure 2: Fortnightly evolution of mean temperature (a, b), Salinity (c, d), dissolved O_2 (e, f), PO_4^{3-} (a', b'), NO_2^- (c', d') and NH_4^+ (e', f') monitored in surface water (3 cm below the surface) at six stations (S1 to S6) of the Oualidia lagoon (Atlantic Coast, northwestern Morocco) during 2011 and 2012.

The higher surface water temperature recorded in upstream stations could be explained by the inflow of warmer freshwater [22]. The rapid temperature decrease recorded throughout the lagoon at the beginning of the survey in May and late June 2011 can be explained by the dredging of a defile and installation of pumping equipment and pressure at sea (part of Oualidia Halieutis project; 2011-2020). The oceanic influence on the surface water lower temperature was noticed throughout the lagoon and especially near the passes (downstream), due to the importance of water exchanges between the lagoon and the coastal ocean Indeed, the important renewal of water in the Oualidia lagoon at each tidal cycle [23], which influence not only the temperature regime, but also the salinity[24]. Salinity showed a seasonal trend in 2011, varying between 22.5 for station S6 (upstream) in summer and 35.9 for station S1 (downstream) in spring (Fig. 2c), with an average of 33.3 (Table 1). In spring-summer 2012 the surface water salinity varied between 23.9 for station S6 (upstream) in summer and 36.3 for station S1 (downstream) in spring, the average value being 33.0 (Fig. 2d, Table 1). The surface water salinity in the Oualidia lagoon increased from upstream to downstream (Figs. 3c, d), was higher in spring 2011 than 2012 and inversely during summer (Table 1). The temperature was negatively correlated with, this correlation being statistically significant (Table 2). Thus, salinity variability in Oualidia lagoon can be explained by homogeneous salinity rate during rising tides where the values are similar to those of the ocean. The freshwater (28% of inputs of continental waters) that permanently flowed into the upstream part of the lagoon [25] can influence the general salinity of the lagoon surface water by decreasing its salinity. Studies conducted by [26] showed similarity with our results.

Table 1: Seasonal variability of physico-chemical parameters and nutrients of surface water of the Oualidia lagoon (Atlantic coast, Morocco) for spring-summer 2011 and 2012.

		Temperature (°C)	**Salinity**	**Dis O_2 (mg/l)**	**PO_4^{3-} (µmol/l)**	**NO_2^- (µmol/l)**	**NH_4^+ (µmol/l)**
Seasons	**Sites**	Mean ± C.I	Mean ± C.I	Mean ± C.I	Mean ± C.I	Mean ± C.I	Mean ± C.I
Spring 2011	**S1**	**18.7±0.3**	**35.6±0.1**	**10.10±0.21 (106.8%)**	**2.2±0.2**	**0.1±0.0**	**2.8±0.3**
	S2	**18.7±0.3**	**35.6±0.1**	**9.88±0.13 (104.5%)**	**2.9±0.1**	**0.1±0.0**	**2.7±0.3**
	S3	**19.4±0.2**	**35.4± 0.0**	**10.40±0.20 (112.3%)**	**2.6±0.2**	**0.2±0.0**	**3.1±0.3**
	S4	**19.6±0.3**	**34.8±0.2**	**11.30±0.50 (122.0%)**	**2.8±0.2**	**0.2±0.1**	**3.0±0.3**
	S5	**20.3±0.3**	**33.3±0.6**	**11.45±0.43 (126.2%)**	**2.9±0.2**	**0.5±0.3**	**2.8±0.3**
	S6	**20.6±0.3**	**32.1±0.8**	**11.92±0.35 (131.4%)**	**3.2±0.2**	**0.6±0.0**	**2.8±0.3**
Summer 2011	**S1**	**17.7±0.1**	**34.5±0.3**	**9.37±0.08 (97.0%)**	**33.2±3.7**	**6.9±0.7**	**27.1±3.1**
	S2	**18.9±0.2**	**33.7±0.4**	**9.44±0.08 (101.9%)**	**37.9±3.6**	**6.2±0.7**	**18.8±2.9**
	S3	**20.2±0.2**	**33.2±0.5**	**9.58±0.05 (105.6%)**	**38.3±3.5**	**7.4±0.7**	**27.6±3.1**
	S4	**20.8±0.2**	**32.0±0.5**	**9.11±0.09 (102.3%)**	**39.4±3.7**	**7.7±0.7**	**27.7±3.4**
	S5	**21.7±0.2**	**30.8±0.5**	**9.00±0.11 (101.1%)**	**37.2±3.2**	**6.9±0.7**	**26.9±3.3**
	S6	**23.1±0.2**	**29.4±0.4**	**8.75±0.18 (102.2%)**	**42.5±3.6**	**7.7±0.7**	**28.0±3.2**
Total average		**19.9**	**33.3**	**10.02 (110.4%)**	**20.4**	**3.7**	**14.4**
Spring 2012	**S1**	**16.2±0.1**	**36.1±0.0**	**8.29±0.12 (84.1%)**	**25.3±3.0**	**6.4±0.6**	**36.1±3.8**
	S2	**16.5±0.1**	**35.3±0.1**	**8.36±0.13 (84.8%)**	**18.7±2.2**	**6.5±0.6**	**35.6±4.0**
	S3	**17.1±0.1**	**34.3±0.1**	**8.52±0.13 (88.2%)**	**21.7±2.4**	**6.6±0.7**	**36.2±3.9**
	S4	**17.4±0.2**	**32.7±0.3**	**8.81±0.12 (91.2%)**	**15.4±2.0**	**7.6±0.6**	**36.5±4.1**
	S5	**18.1±0.2**	**30.8±0.4**	**8.32±0.25 (88.0%)**	**17.5±2.3**	**7.5±0.6**	**36.7±4.0**
	S6	**18.6±0.3**	**29.2±0.4**	**9.14±0.13 (96.7%)**	**16.7±2.2**	**7.7±0.5**	**37.3±4.1**
Summer 2012	**S1**	**16.6±0.1**	**35.1±0.2**	**9.02±0.06 (91.5%)**	**22.5±3.3**	**5.8±0.7**	**25.7±2.7**
	S2	**17.4±0.1**	**34.9±0.2**	**9.05±0.06 (93.7%)**	**19.4±3.3**	**10.7±0.8**	**21.4±2.4**
	S3	**18.8±0.2**	**34.1±0.2**	**9.17±0.03 (99.0%)**	**24.3±3.2**	**7.1±0.9**	**23.3±2.7**
	S4	**20.5±0.2**	**32.8±0.3**	**8.94±0.04 (98.5%)**	**20.5±3.5**	**10.4±0.9**	**23.1±2.9**
	S5	**22±0.4**	**31.3±0.4**	**8.82±0.06 (101.1%)**	**19.2±3.1**	**7.4±0.7**	**23.6±2.8**
	S6	**22.2±0.3**	**29.7±0.4**	**8.82±0.08 (101.1%)**	**18.2±3.3**	**7.8±0.7**	**24.7±2.7**
Total average		**18.4**	**33.0**	**8.77 (92.8%)**	**20.0**	**7.6**	**28.1**

The Oualidia lagoon surface water was well oxygenated in spring 2011-2012 with a minimum value of 9.1 mg/l (96.3.0%) for station S2 and a maximum value of 10.5 mg/l (114.8%) for station S6 (upstream; Fig. 2e) with an average of 10.02 mg/l (110.4%) (Table1). In summer 2011-2012 the surface water dissolved O_2 varied between a minimum of 8.8 mg/l (102.8%) for station S6 and a maximum 9.4 mg/l (101.5%) for station S3 (Fig. 2f), the average value being 8.77 mg/l (92.8%) (Table 1). The surface water dissolved O_2 in the Oualidia lagoon increased from upstream to downstream in summer and decreased in spring (Figs. 3e,f). In spring 2011-2012 dissolved O_2 levels were higher than those recorded in summer 2011-2012. The dissolved O_2 was positively correlated with temperature, this correlation being statistically significant (Table 2).

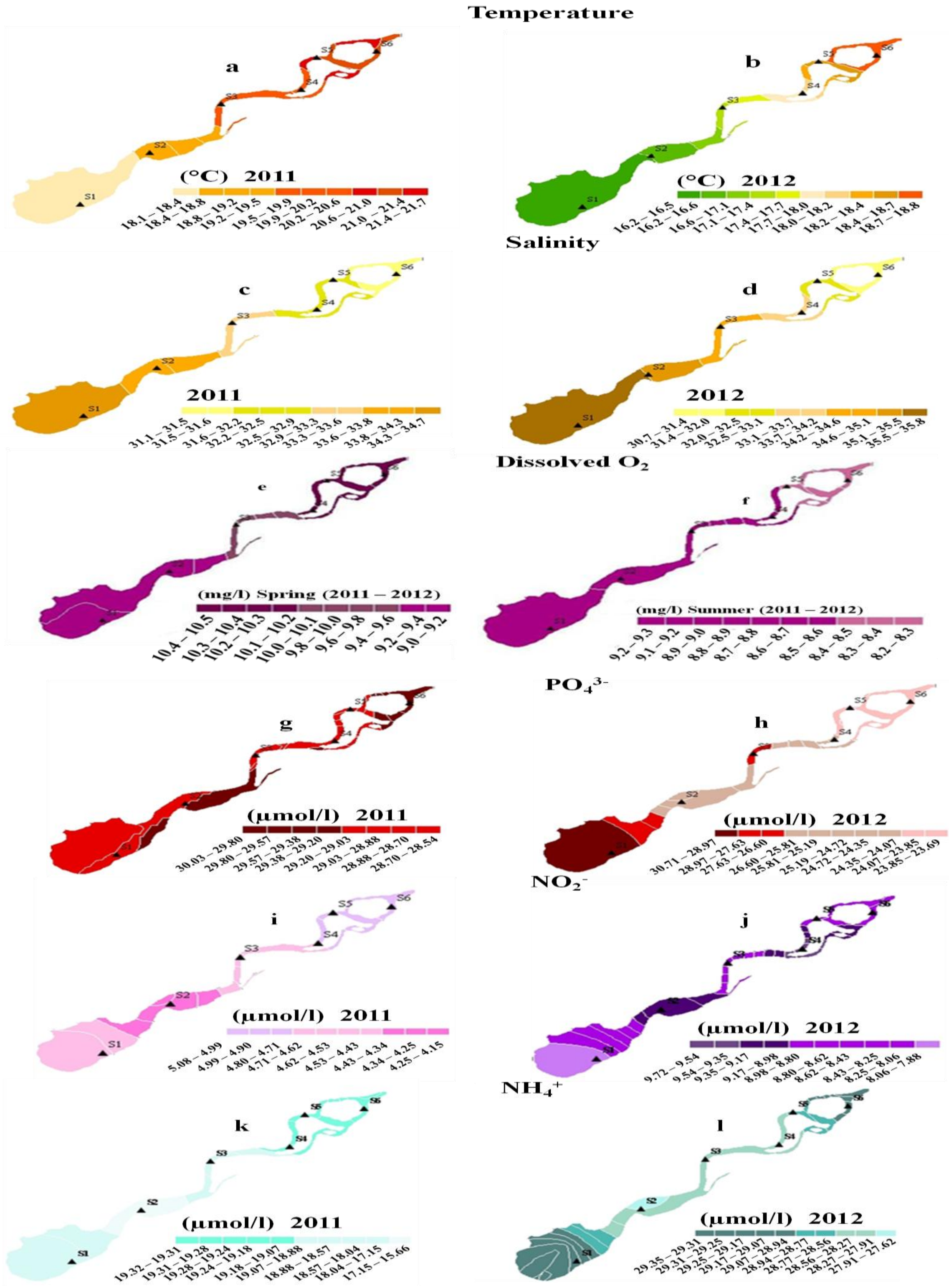


Figure 3: Spatial variability of physico-chemical parameters (Temperature (°C): **a** and **b**; Salinity: **c** and **d** during spring-summer 2011 and 2012; Dissolved O_2 (mg/l): **e** (spring 2011-2012) and f (summer 2011-2012) and nutrients (µmol/l; PO_4^{3-} : **g** and **h**; NO_2^-: **i** and **j**; NH_4^+: **k** and **l**) monitored in surface water (from the first 10 cm water surface) of the Oualidia lagoon (Atlantic Coast, northwestern Morocco) during spring-summer 2011 and 2012.

Globally, the agitation of the surface water, the upstream freshwater supply [25] and the low bathymetry of Oualidia lagoon are the possible factors contributing to the good oxygenation of the water body. The analysis of dissolved O_2 at our study revealed a subdivision of the Oualidia lagoon into two distinct parts in spring: a less oxygenated zone downstream (S1, S2, S3) and a more oxygenated one upstream (S4, S5, S6). That spring gradient was inversed in summer. These results were compatible with previous works on the lagoon [17], and could be explained by the influence of oceanic surface water. Indeed, downstream dissolved O_2 levels were similar to those measured in the open ocean. Regarding the higher values of dissolved oxygen measured upstream, they resulted from the spring phytoplankton bloom [16]. The dissolved O_2 values gradually decreased during the period post-bloom, probably due to the increased respiration of organisms (i.e. the degradation of organic matter by aerobic heterotrophic bacteria) and the summer water temperature increase that limits the dissolution of O_2.

Table 2: Spearman correlation matrix between physico-chemical parameters (T: temperature; Sal: salinity and Dis O_2: dissolved oxygen) and nutrients (PO_4^{3-} : orthophosphates; NO_2^- : nitrite and NH_4^+: ammonium) of surface water of the Oualidia lagoon (Atlantic coast, Morocco)**.**

	T (°C)	Sal	dis O_2 (mg/l)	PO_4^{3-} (µmo/l)	NO_2^- (µmo/l)	NH_4^+ (µmol/l)
T (°C)	1.000	-.546**	.236**	-.075	-.193**	.107
		.000	.001	.274	.005	.116
		197	198	216	214	216
Sal		1.000	-.037	-.107	-.105	-.224**
			.610	.136	.141	.002
			197	197	197	197
Dis O_2 (mg/l)			1.000	-.388**	-.172*	-.167*
				.000	.015	.019
				198	198	198
PO_4^{3-} (µmo/l)				1.000	.496**	.213**
					.000	.002
					214	216
NO_2^- (µmo/l)					1.000	.404**
						.000
						214
NH_4^+ (µmol/l)						1.000

** The correlation is significant at the 0.01 level (bilateral).
* The correlation is significant at the 0.05 level (bilateral)

3.2. *Distribution of nutrients*

Surface water PO_4^{3-} concentrations varied in the Oualidia lagoon in spring-summer 2011 from a minimum of 0.7 µmol.l^{-1} in spring for station S1 (downstream) to a maximum of 89.4 µmol.l^{-1} in summer for station S4 (upstream) (Fig. 2a'), the average value being 20.4 µmol.l^{-1} (Table 1). In spring-summer 2012 surface water PO_4^{3-} concentrations fluctuated between a minimum of 0.1 µmol.l^{-1} in spring for station S6 (upstream) and a maximum of 79.8 µmol.l^{-1} in summer for station S4 (upstream; Fig. 2b'), the average value being 19.9 µmol.l^{-1} (Table 1). A decreasing gradient from upstream to downstream was recorded for that nutrient (Figs 3g,h). Surface water PO_4^{3-} concentrations recorded in spring-summer 2012 were similar to those of 2011 (Table 1). In the present study, measured PO_4^{3-} concentrations were higher than those recorded for NO_2^- and NH_4^+. This finding could confirm the influence of oceanic water, which is the main source of phosphate for coastal waters. The PO_4^{3-} concentration was positively correlated with NO_2^- and NH_4^+ and negatively correlated with dissolved O_2 (Table 2), these three correlations being statistically significant (Table 2). The higher PO_4^{3-} values and the low dissolved O_2 concentrations reported during summer periods could be related to reduced primary production rates. The presence of higher concentration of nutrients is due to the influence of muddy sediment of shallow depth of the lagoon [27] . Moreover, leaching agriculture areas, which are rich in phosphate fertilizers and the presence of phosphate mine between the two Moroccan cities El jadida and Safi [28] potentially, contribute to the water quality of the interior part of the lagoon. PO_4^{3-} enrichments of surface waters noted in Oualidia lagoon were higher those recorded in other lagoon (Table 3).

NO_2^- surface water concentrations varied in spring-summer 2011 from a minimum of 0.1 µmol.l^{-1} in spring for station S1 (downstream) to a maximum of 18.4 µmol.l^{-1} in summer for station S6 (upstream) (Fig. 2c'), the average value being 3.7 µmol.l^{-1} (Table 1). In spring-summer 2012 water surface NO_2^- concentrations fluctuated between a minimum of 0.04 µmol.l^{-1} in spring for station S4 and a maximum of 19.6 µmol.l^{-1} in summer for stations S2 and S4 (Fig. 2d'), the average value being 7.6 µmol.l^{-1} (Table 1). A decreasing gradient from upstream to downstream was recorded for that nutrient (Figs 3i,j). NO_2^- concentrations were higher in spring 2012 compared to spring 2011 and similar during the summer period of both years (Table 1). The NO_2^- concentration was positively correlated with NH_4^+ and negatively correlated with dissolved O_2 (Table 2), these correlations being statistically significant (Table 2). The analysis results of this study clearly showed higher maximum nitrogen concentration in Oualidia lagoon in comparison with other coastal waters (Table 3), although relative scarcity of these elements near the lagoon passes during the study period were noticed. The spatial variation of NO_2^- could be explained by an important sediment-water exchange in the downstream lagoon. This feature disadvantages the residence time of nitrifying bacteria and causes the inhibition of nitrification [29] . This is particularly the case in the upstream lagoon, characterized by lower depth and further influenced by continental inputs (fertilizers, mudflat...). The lowest value of NO_2^- was recorded downstream and this can be caused by freshwater runoff between S1 and S2 (34 springs) [25] that makes dilution of the seawater. The seasonal variation showed that the highest NO_2^- values observed in summer might be controlled by phytoplankton and zooplankton excretion. NH_4^+ surface water concentrations varied in 2011 between a minimum of 0.1 µmol.l^{-1} in spring for station S1 (downstream) and a maximum of 74.1 µmol.l^{-1} in summer for station S5 (upstream) (Fig. 2e'), the average value being 14.4 µmol.l^{-1} (Table 1). In spring-summer 2012 the lowest NH_4^+ concentration of 0.2 µmol.l^{-1} was recorded in summer for station S5 (upstream) and the highest one of 100.3 µmol.l^{-1} in spring for station S6 (upstream) (Fig. 2f'), the average value being 28.1 µmol.l^{-1} (Table 1). The lagoon surface water NH_4^+ concentration showed a decreasing trend from upstream to downstream, except for the southern lagoon-side stations S1 and S2 (Figs 3k,l). NH_4^+ concentrations were higher in spring 2012 compared to spring 2011 and inversely during the summer period, except for station S2 summer sample (Table 1). The NH_4^+ concentration was negatively correlated with dissolved O_2 and salinity (Table 2), these correlations being statistically significant (Table 2). Recorded higher concentration of NH_4^+ could be partially due to the death and subsequent decomposition of phytoplankton, secondly to the excretion of ammonia by planktonic organisms [30] and summer tourism. Our results remain close to those registered in Nador lagoon [31]. The nutrient concentrations recorded in this work clearly show a significant increase from summer 2011. That increase could be explained by sediment resuspension [32], by the start of the Oualidia Halieutis project activities from May 2011 (dredging of a defile and installation of pumping equipment and waste water treatment).

Table 3: Comparison of hpysico-chemical parameter values and nutrient levels between surface water of lagoons of the African Atlantic coast.

Sites	T (°C)	Dissolved O2 (mg/l)	Salinity	NH_4^+ (µmol/l)	P (µmol/l)	NO_2^- (µmol/l)	References
Oualidia lagoon (Morocco)	Min=17.0 ; Max= 21.0	Min=4.80; Max=13.78	Min=24.8; Max=36.3	Min=0.187; Max=100.5	Min=0.031; Max=43.174	Min=0.002; Max=19.557	This study
Massa lagoon (Morocco)	Min=16.1; Max=25.0	Min=3.00; max=6.36	Min=12.0; Max=24.6	255.000	Min=0.273; Max=1.977	nd	[33]
Aghien lagoon (Ivory Coast)	Min=31.8 Max=33.0	Min=3.60 Max=6.70	Min=0.0 Max=0.1	Min=450.000 Max=3150.000	Min=0.000 Max=4.523	Min=0.043 Max=0.130	[34]

3.3. *PCA analysis*

PCA analysis of physico-chemical parameters and nutrients data showed that, for all 6 stations monitored during spring-summer 2011 and 2012, the joined input of the first two axes explained 97.25% of the total variability of the correlation matrix. Axis1 accounted for 58.85% of the variability and was essentially a combination of NO_2^-, PO_4^{3-}, NH_4^+ and temperature. Axis 2 accounted for 38.37% of the variability, and was mainly a combination of dissolved O_2 concentrations and salinity. Seasonal variability was mainly recorded along axis 1, with spring and summer 2012 samples located in the direction of increasing NO_2^-, PO_4^{3-}, NH_4^+ concentrations and temperature and spring and summer 2011 samples in the direction of increasing salinity and dissolved O_2 (Fig. 4).

The results of the principal component analysis (PCA) showed a low inter-stations variability of hydrological parameters and nutrients concentration. Different water masses are mixed by the lagoon dynamics that most probably prevent the establishment of a vertical stratification (although not monitored) and lead to the observed upstream-downstream decreasing gradient of the investigated variables. Unlike, the spatial variation, the measured parameters showed significant seasonal variations (Fig. 4). A significant station variation was observed in temperature, salinity and dissolved O_2. This finding reveals that the waters of Oualidia lagoon define two ecological entities:

Zone 1 represented by stations 1 and 2, marked by oceanic influence. Zone 2 represented by stations 3, 4, 5 and 6, influenced by the presence of fresh water resurgence and anthropogenic activities.

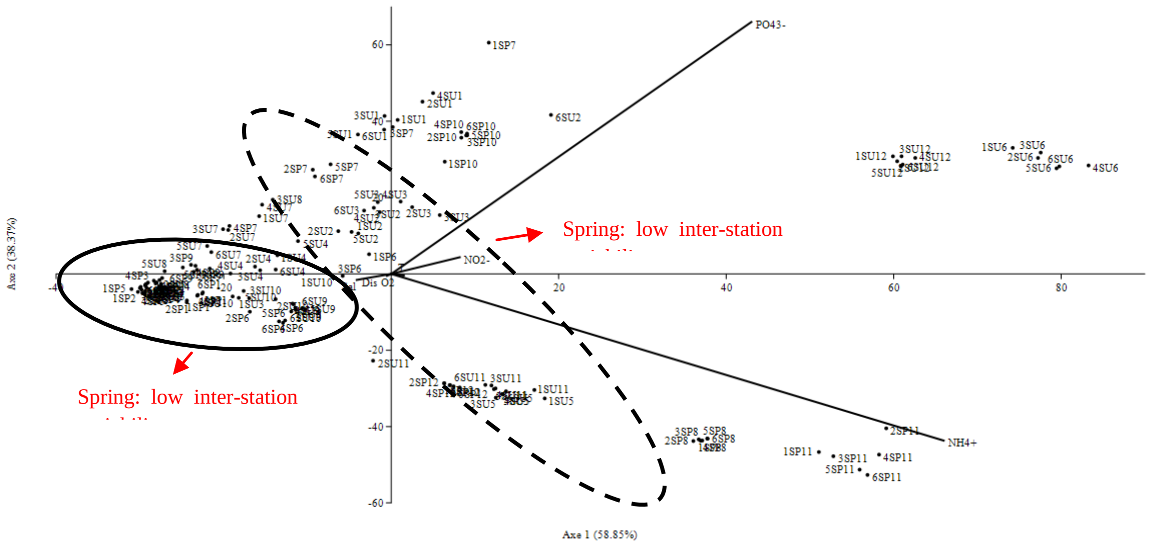


Figure 4: Principal component analysis (PCA) of physico-chemical parameters and nutrients monitored in surface water (to 10 cm) of the Oualidia lagoon (Atlantic Coast, northwestern Morocco) during spring (SP)-summer (SU) 2011 and 2012 at 6 stations (xSP or xSU, x being respectively equal to 1, 2, 3, 4, 5 or 6). Factorial variables: Axe 1 (58.85%) and Axe 2 (38.37%). Bold lines: variables according to spatial and temporal variability. T: temperature, Dis O_2: dissolved oxygen, Sal: Salinity, PO_4^{3-}: orthophosphates, O_2^-: nitrite, NH_4^+: ammonium.

Conclusion

Short-term variability of environmental variables (physico-chemistry and nutrient loadings) has rarely been documented in African Atlantic coastal water bodies.

This present study shows a richness of nutrient of Oualidia lagoon, with a seasonal variability and low spatial variability. The higher nutrient concentration of Oualidia lagoon surface water recorded from summer 2011 was due to increasing human activities (intense agricultural, fishing and tourism activities and Oualidia Halieutis project 2011-2020 construction).

Results presented in this study provide a good example of lagoon ecological study in Morocco. It provided pioneer information on the spatial and seasonal changes of water quality parameters in the Oualidia lagoon. Our results indicated that this lagoon is an interesting, but exploited aquatic system than can therefore be weakened. That system thus needs further study as well as a scientific management plan in order to avoid its environmental degradation. In order to prevent drastic and potentially irreversible changes to the ecological character of the Oualidia lagoon, temporal trends in nutrient (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}, but also Si) and biological (phytoplankton and zooplankton) dynamics should be continuously monitored.

The data collected in this study will be useful to conceptualize the functioning of Oualidia lagoon ecosystem, using the measured state variables and forcing parameters, to develop the first ecological model of a Moroccan coastal zone.

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