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Assessment of Primary Production in an Estuarine Environment – The Case of the Oum Er Rbia Estuary (Atlantic Coast, Morocco)

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ABSTRACT

Variations in primary production in relation to selected physicochemical and biological parameters of the Oum Er Rbia River estuary were measured monthly from November 2018 to January 2020 at two stations using the clear and dark bottle method. Gross primary production (GPP) ranged from 9.28 to 467.07 mg C/m^3/h; net primary production (NPP) ranged from 3.09 to 248.13 mg C/m^3/h; and respiration (R) ranged from 4.03 to 262.73 mg C/m^3/h. GPP, NPP and R are lowest in summer, increasing to peak in spring. In summer and winter, significantly positive correlations were observed between GPP and NPP on the one hand, and phaeopigments on the other. In summer, there is also a significant positive correlation between respiration and dissolved oxygen concentration. In winter, significant negative correlations were found between conductivity and salinity, on the one hand, and GPP, and in summer and winter, on the other, with NPP. Spatial and seasonal variations in productivity depend on the environmental and meteorological conditions at each station, including water temperature, salinity, conductivity, nutrient inputs and light availability.

Keywords: primary production, estuary, Oum Er Rbia, Morocco.

INTRODUCTION

Primary production in aquatic environments refers to the quantity of organic carbon produced within a given unit of time and space, resulting from the transformation of inorganic carbon via the process of photosynthesis by photosynthetic organisms (phytoplankton and algae) present in aquatic ecosystems such as oceans, lakes and rivers (Falkowski and Raven, 2007). The organic matter thus produced forms the basis of trophic chains and sustains life within these ecosystems (Cloern et al., 2014). Assessing primary production in aquatic ecosystems is crucial to understanding how these environments function, conserving biodiversity, managing natural resources sustainably and minimizing the impact of environmental change. Several methods can be used to estimate primary production in water:

- Winkler bottle method, which involves incubating a water sample in the dark to determine the concentration of dissolved oxygen before and after incubation, enabling photosynthesis and respiration to be estimated (Strickland and Parsons, 1968).
- Pulse-induced fluorescence method, which uses fluorescence sensors to measure the intensity of chlorophyll-a fluorescence to estimate photosynthesis (Behrenfeld and Falkowski, 1997).
- Radioisotope bottle incubation method where radioactive isotopes such as carbon-14 (14C) are used to trace carbon incorporation into plant biomass during photosynthesis (Nielsen, 1952).
- A method of measuring dissolved oxygen and carbon, involving the measurement of oxygen consumption and carbon dioxide production by the processes of respiration and photosynthesis (Odum and Hoskin, 1958).
- Numerical models based on biological and environmental data are used to estimate primary production in aquatic ecosystems (Platt et al., 2003).

Few works have addressed primary production in Morocco's coastline (Bessa et al., 2018; Bozzano and Alonso 2009; Eberwein and Mackensen 2006; Head et al., 1996; Santana-Falcón et al., 2016) and even fewer in Moroccan rivers and wetlands (Bocci et al., 2016; Elkhiati et al., 2013). In order to identify the water quality of the Oum Er Rbia estuary on the basis of water parameters and primary productivity, eight water parameters (temperature, salinity, conductivity, dissolved oxygen, pH, chlorophyll-a, phaeopigments, Secchi depth) their temporal and spatial distribution, and primary productivity (gross primary production (GPP), net primary production (NPP), respiration (R)) were monitored monthly from November 2018 to January 2020 at two stations in the Oum Er Rbia estuary at a depth of two meters.

MATERIALS AND METHODS

Description of the study area

The Oum Er Rbia is one of Morocco's major rivers, with a length of around 555 kilometers and a watershed covering an area of some 40000 km^2. It rises in the Middle Atlas Mountains, near the town of Khénifra, and flows through a variety of regions, from mountains to coastal plains, before emptying into the Atlantic Ocean near the town of Azemmour. In this study, we carefully selected two stations along the estuary (Figure 1).Station 1 = S1 (33° 16' 44" N; 8° 19' 50" W): upstream station, located between the second and third bridges, about 2.2 km upstream of the main discharge from the town of Azemmour, 3 km from station 2 and 4.7 km from the mouth, with an average depth of 4.92 m at high tide. Station 2 = S2 (33° 18' 21" N; 8° 20' 23" W): Downstream station, 1 km from the discharge and 1.7 km upstream of the mouth, with an average depth of 4 m at high tide.

Primary production parameters

Primary production was measured monthly from November 2018 to January 2020 using the clear and dark bottle method (Gaarder and Gran 1927). Water sampling was carried out at a depth of two meters using a six-liter capacity Niskin bottle. Three 300 ml Winkler flasks were filled with water. Two bottles are clear and transparent, while the third is dark and wrapped in black adhesive tape. The first clear bottle is immediately fixed for oxygen determination at the time of sampling. The other two vials were attached to a float by a rope and incubated for 4 hours at the original depth. After the incubation time, the clear and dark vials were lifted from the water and fixed for determination of their oxygen content. Dissolved oxygen was determined using Winkler's volumetric method (Aminot and Chaussepied, 1983). Oxygen values (mg/L) were

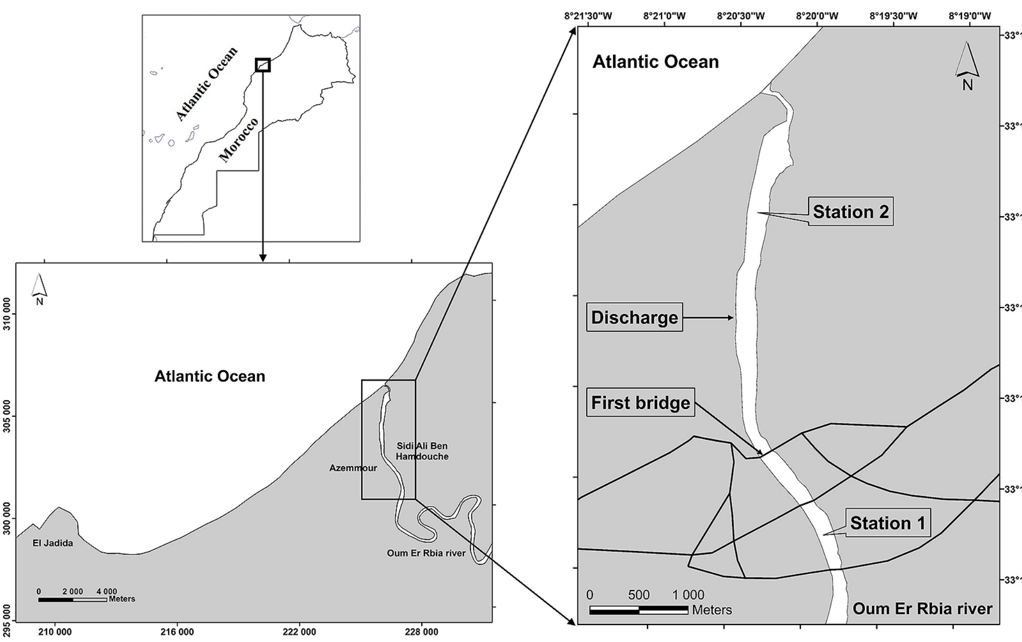

Figure 1. Location of sampling stations in the Oum Er Rbia estuary

converted to carbon values by applying the equations proposed by Wetzel and Likens (2000):

$$Gross\ primary\ production\ (GPP) = \frac{(CB-DB)(1000)(0.375)}{(PQ)(t)}\ (\text{mg C/m}^3/\text{h}) \quad (1)$$

$$Net\ primary\ production\ (NPP) = \frac{(CB-IB)(1000)(0.375)}{(PQ)(t)}\ (\text{mg C/m}^3/\text{h}) \quad (2)$$

$$Respiration\ (R) = \frac{(IB-DB)(RQ)(1000)(0.375)}{t}\ (\text{mg C/m}^3/\text{h}) \quad (3)$$

where: CB – dissolved oxygen in the clear bottle,
DB – dissolved oxygen in the dark bottle,
IB – dissolved oxygen in the initial bottle,
t – hours of incubation.

PQ and RQ represent the photosynthetic and respiratory quotients respectively, corresponding to the oxygen and carbon molecules used or produced during photosynthesis and respiration. Since PQ and RQ values vary according to algal species, their chemical composition and environmental conditions (Strickland 1966), mean values of 1.2 and 1.0 were respectively obtained from algal populations exposed to moderate light intensities.

Physicochemical and chlorophyll parameters

Air temperature was measured by a mercury thermometer ranging from 0 to 100 °C. Water temperature, salinity, conductivity and pH were measured using a WTW 340i multi-parameter analyzer. Chlorophyll-a and phaeopigments were determined spectrophotometrically using the protocol proposed by Aminot and Chaussepied (1983). Water transparency was measured visually by determining the depth of disappearance of a standard 25 cm diameter Secchi disc using a graded string.

Statistical analysis

The correlation coefficient and corresponding probable error (Pearson and Filon 1898) were calculated to establish the relationship between the variables (water and air temperature, Secchi depth, conductivity, salinity, pH, chlorophyll-a, phaeopigments and dissolved oxygen) and the dependent variables (GPP, NPP and R) both by station and season, as well as a two-way analysis of variance (station x season) of the dependent variables. Graphical representations and statistical analysis were performed using the freeware R (R Core Team, 2023) and the packages ggplot2 (Wickham 2016), readxl (Wickham and Bryan 2023), ggpubr (Kassambara 2023), forcats (Wickham 2023).

RESULTS

Physicochemical and chlorophyll parameters

Air temperature in S1 ranged from 11.40 °C in January 2020 to 23 °C in June, July and August 2019 with an average of 16.81 °C, while in S2 its values ranged from 13.20 to 24 °C in September 2019 and January 2020, respectively, with an average of 19.28 °C (Figure 2A).

Water temperature closely follows atmospheric temperature variation and oscillated between 15.10 °C and 25.60 °C in S1 and between 15.30 °C and 22.90 °C in S2, averaging 19.74 °C and 18.98 °C respectively over the study period with S1 values exceeding those of S2 between March 2019 and October 2019. Minimum temperatures were recorded in January 2020 for both stations, while maximum temperatures were recorded in July 2019 for S1 and May 2019 for S2 (Figure 2B). The Secchi depth used to determine the depth of vertical light penetration into the water varied in this study from a minimum of 30 cm and 40 cm in March and May 2019 to a maximum of 430 cm and 340 cm in January 2020 and September 2019 with mean values of 187.3 and 192.5 cm in S1 and S2, respectively (Figure 2C).

Salinity shows the same pattern in both stations and varied between 21.50‰ and 35.70‰ in S1 and between 26.0‰ and 35.9‰ in S2, with an average of 32.35‰ in S1 and 34.2‰ in S2 over the study period. The minimum salinity values were observed in November 2018 for both stations and the maximum values in August 2019 for S1 and July 2019 for S2 (Figure 3A). The variations in conductivity perfectly resemble those in salinity, with a minimum of 34.7 µS/cm and 41.1 µS/cm recorded in November 2018 and a maximum of 54.2 µS/cm and 54.7 µS/cm recorded in October 2019 at S1 and S2 respectively. The respective mean values during the study period are 49.86 µS/cm and 52.41 µS/cm (Figure 3B). The high salinity and conductivity values recorded during this study show that the Oum Er Rbia estuary is dominated by the sea (no connection with freshwater). The lower values observed in November 2018 are probably due to dilution of the water in the estuary as a result of the heavy rainfall recorded that month.

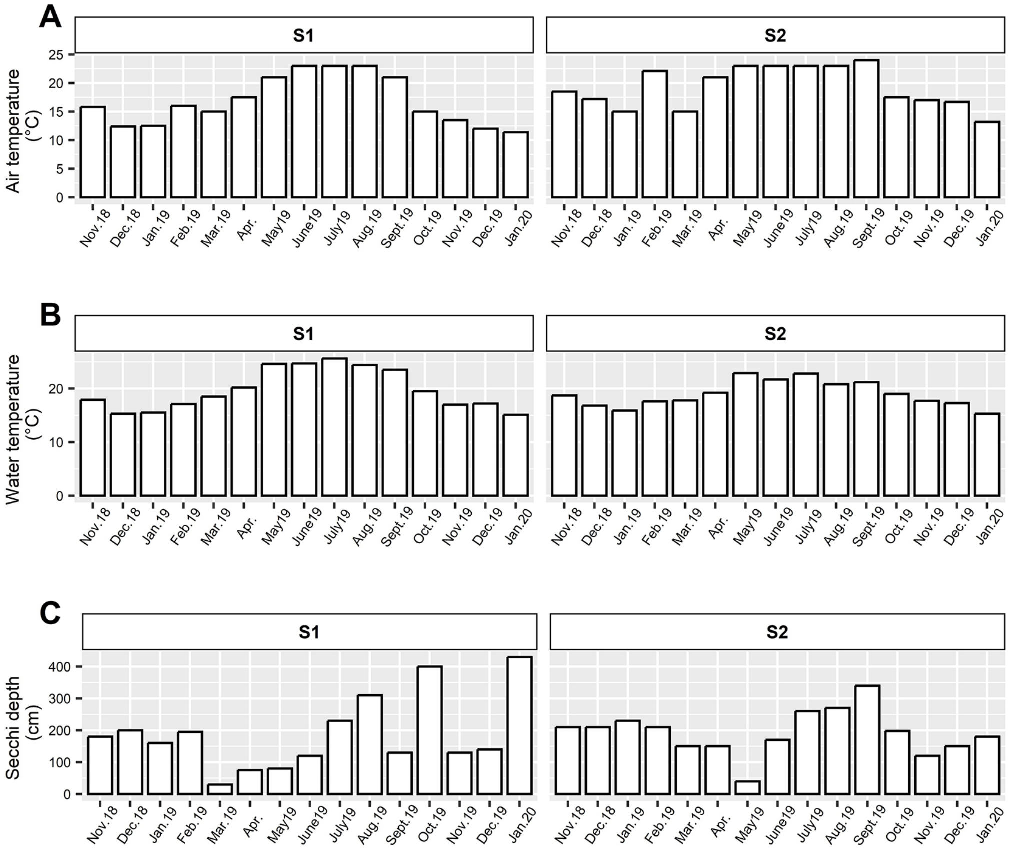

Figure 2. Monthly variations of environmental parameters at the two stations of the Oum Er Rbia estuary, during the period November 2018 – January 2020: (a) air temperature, (b) water temperature, (c) Secchi depth.

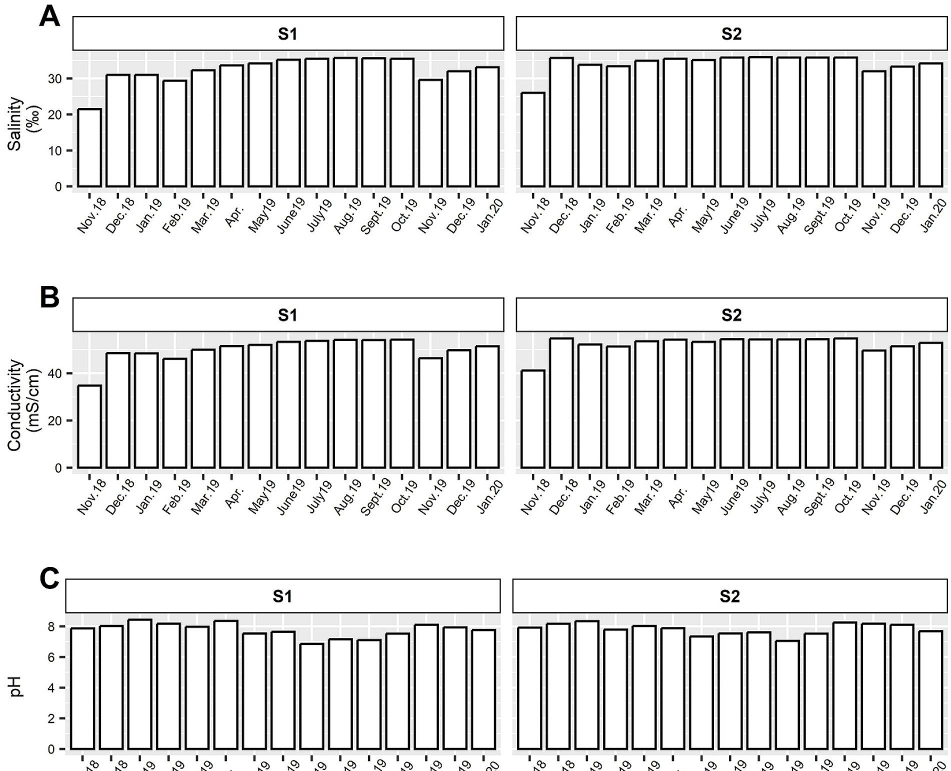

Figure 3. Monthly variations of environmental parameters at the two stations of the Oum Er Rbia estuary, during the period November 2018 – January 2020: (a) salinity, (b) conductivity, (c)pH.

Fluctuations in pH ranged from slightly acidic to moderately alkaline. The lowest pH values were 6.86 in S1 and 7.05 in S2 and were recorded in July and August 2019 respectively, while the highest values were 8.43 and 8.34 and were recorded in January 2019 with mean values of 7.76 and 7.82 respectively (Figure 3C).

With the exception of a peak in March 2019 at station S1 (14.69 mg/m^3, 365.12 mg/m^3 and 379.81 mg/m3), the values for chlorophyll-a, phaeopigments and total chlorophyll changed only within a narrow range (0–3.05; 0.76–31.35 and 0.76–34.40 mg/m^3 in S1 compared with 0–3.66; 1.70–6.73 and 1.70–10.39 mg/m^3 in S2) with values in S1 slightly exceeding those in S2 throughout most of the study period (Figure 4A, 4B).

The variation in dissolved oxygen at the two study stations followed a very distinct seasonal pattern. Dissolved oxygen levels fluctuated between minimum values recorded in spring, with 0.63 mg/L in S1 and 3.9 mg/L in S2, and maximum values in summer for S1 and winter for S2, which reached 7.59 mg/L and 8.22 mg/L respectively. The average over the study period was 4.65 mg/L for S1 and 6.36 mg/L for S2, showing marked seasonal variations in dissolved oxygen content (Figure 4C).

Primary production parameters

With the exception of three very distinct peaks in March 2019 at S1 (187.88 mg C/m^3/h) and April and November 2019 respectively at S2 (183.56 and 467.07 mg C/m^3/h), the mean range of GPP varied from 9.28 to 95.65 mg C/m^3/h at S1 and 32.37 to 67.50 mg C/m^3/h at S2 with slightly higher values in S1 in more than half the months of the study period (Figure 5A). NPP ranged from 3.09 to 80.59 mg C/m^3/h in S1 and from 8.42 to 248.13 mg C/m^3/h in S2, with the lowest values recorded in July and September 2019 and the highest values in November and April 2019 in S1 and S2 respectively (Figure 5B).GPP and NPP were lowest during the summer, and started to increase in autumn and winter to reach their maximums in spring (Figure 5A, 5B). The mean range of R varied from 4.03 to 130.76 mg C/m3/h in S1 and from 9.71 to 262.73 mg C/m^3/h in S2, with minimum values recorded in November 2018 and 2019 and maximum values in March and April 2019 for S1 and S2 respectively. Like GPP and NPP, R was minimum in summer, average in autumn and winter and maximum in spring (Figure 5C).

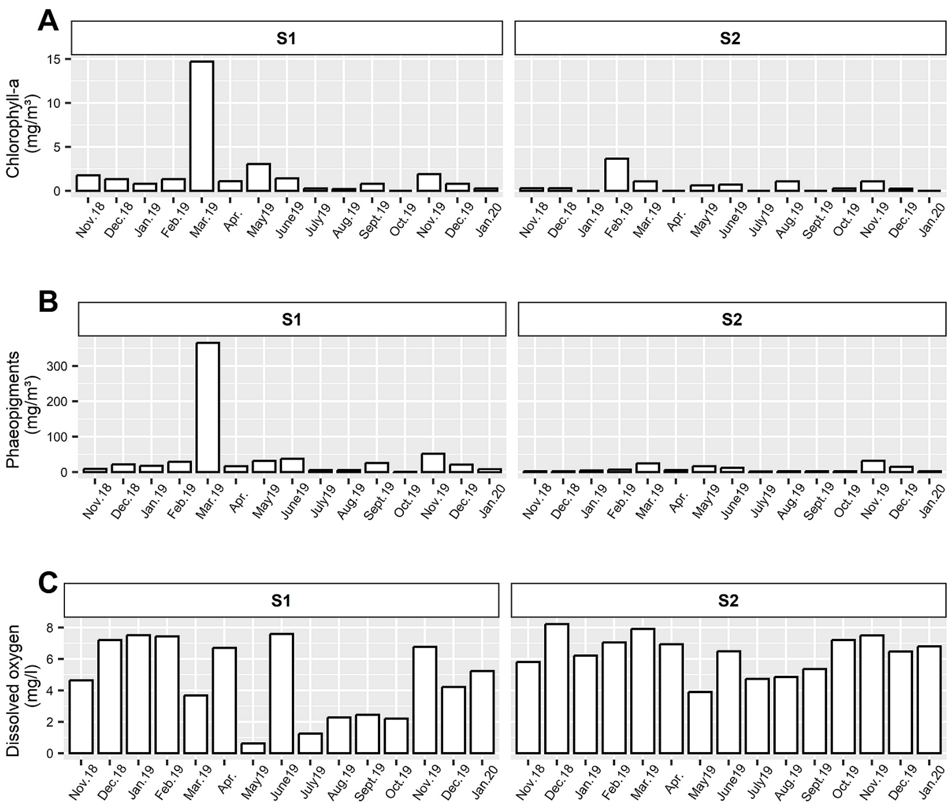

Figure 4. Monthly variations of environmental parameters at the two stations of the Oum Er Rbia estuary, during the period November 2018–January 2020: (a) chlorophyll-a, (b) phaeopigments, (c) dissolved oxygen.

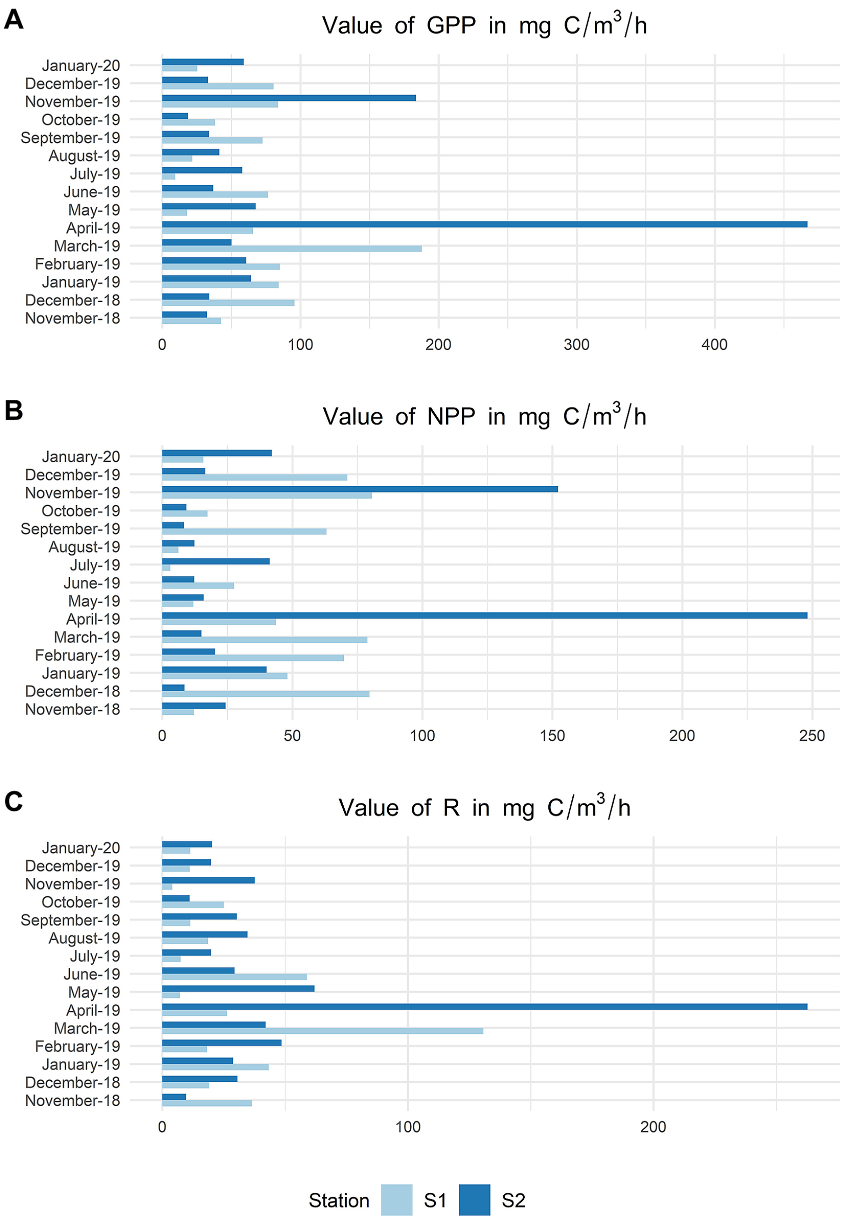

Figure 5. (a) Monthly variation of GPP in the two stations of the Oum Er Rbia estuary from November 2018 to January 2020; (b) Monthly variation of NPP in the two stations of the Oum Er Rbia estuary from November 2018 to January 2020; (c) monthly variation of R in the two stations of the Oum Er Rbia estuary from November 2018 to January 2020.

Statistical analysis

Based on the criterion that the value of the correlation coefficient is only significant if it is more than six times greater than the probable error (r > 6 PE), GPP, NPP and R did not correlate significantly with the environmental parameters at station S2. At station S1, significant positive correlations were observed between GPP and chlorophyll pigments (r = 0.767 and PE = 0.072 for chlorophyll-a, r = 0.809 and PE = 0.060 for phaeopigments) and between R and chlorophyll pigments (r = 0.859 and PE = 0.046 for chlorophyll-a, r = 0.870 and PE = 0.042 for phaeopigments) (Table 1). No significant correlations were observed between GPP, NPP and R with the environmental parameters in autumn and spring during the study period. Significant positive correlations were observed between GPP and phaeopigments in summer (r = 0.72 and PE = 0.12), between NPP and phaeopigments in winter (r = 0.75 and PE = 0.09) and between R and dissolved oxygen in summer (r = 0.88 and PE = 0.05). Significant

Table 1. Correlation coefficients (r) and probable errors (PE) for GPP, NPP and R based on environmental parameters at the two stations in the Oum Er Rbia estuary during the study period.

Parameters		Station 1			Station 2		
		GPP	NPP	R	GPP	NPP	R
Air temperature	r	-0.378	-0.511	-0.057	0.072	-0.032	0.199
	PE	0.149	0.129	0.174	0.173	0.174	0.167
	r/PE	-2.532	-3.971	-0.328	0.416	-0.184	1.190
Water temperature	r	-0.402	-0.528	-0.077	-0.024	-0.099	0.075
	PE	0.146	0.126	0.173	0.174	0.172	0.173
	r/PE	-2.753	-4.204	-0.445	-0.138	-0.574	0.433
Secchi depth	r	-0.564	-0.491	-0.390	-0.286	-0.284	-0.259
	PE	0.119	0.132	0.148	0.160	0.160	0.162
	r/PE	-4.749	-3.715	-2.641	-1.789	-1.774	-1.594
Salinity	r	-0.177	-0.194	-0.078	0.071	-0.035	0.201
	PE	0.169	0.168	0.173	0.173	0.174	0.167
	r/PE	-1.049	-1.158	-0.451	0.410	-0.201	1.203
Conductivity	r	-0.151	-0.154	-0.080	0.077	-0.024	0.200
	PE	0.170	0.170	0.173	0.173	0.174	0.167
	r/PE	-0.887	-0.906	-0.462	0.445	-0.138	1.196
pH	r	0.523	0.555	0.250	0.094	0.187	-0.037
	PE	0.127	0.121	0.163	0.173	0.168	0.174
	r/PE	4.134	4.605	1.531	0.545	1.113	-0.213
Chlorophyll-a	r	**0.767**	0.373	**0.859**	-0.104	-0.130	-0.060
	PE	**0.072**	0.150	**0.046**	0.172	0.171	0.174
	r/PE	**10.697**	2.488	**18.817**	-0.604	-0.759	-0.346
Phaeopigments	r	**0.809**	0.425	**0.870**	0.153	0.243	0.021
	PE	**0.060**	0.143	**0.042**	0.170	0.164	0.174
	r/PE	**13.444**	2.978	**20.549**	0.900	1.483	0.121
Dissolved oxygen	r	0.421	0.506	0.134	0.166	0.212	0.090
	PE	0.143	0.130	0.171	0.169	0.166	0.173
	r/PE	2.938	3.905	0.783	0.980	1.275	0.521

negative correlations were observed for GPP in winter (r = -0.74 and PE = 0.10 for conductivity and salinity) and for NPP in winter and summer (r – -0.76 and PE – 0.09 for conductivity, r = -0.77 and PE = 0.09 for salinity, r = -0.79 and PE = 0.09 for air temperature) (Table 2). A two-way analysis of variance (ANOVA) was performed to highlight the effect of season and station on primary production. No significant differences were found in the three components (GPP, NPP and R) with respectively (p = 0.511, 0.483 and 0.4892), when season and station were considered together at the 5% significance level ($p > 0.05$), but when they were considered separately on the basis of stations and seasons, there were significant differences at the 5% significance level ($p < 0.05$) only in the case of R for the season factor (Table 3).

DISCUSSION

Temperature is one of the most important variables in the living environment, influencing a wide range of other factors that directly or indirectly affect living organisms (Hauer and Hill, 2007), and plays an important role in the biological cycles that affect fisheries (Aminot and Chaussepied, 1983). The water temperature results obtained in this study are comparable with other studies carried out on similar ecosystems in Morocco: in the Oum Er Rbia estuary, mean values range between 16.77 °C and 25.35 °C and are related to local conditions (climate, sunshine duration, flow rate) and the recorded deviations can be explained by the daily time difference between the different sampling points (Asfers et al., 2017) while in the upstream part of the river

Table 2. Correlation coefficients (r) and probable errors (PE) for GPP, NPP and R with environmental parameters by season in the Oum Er Rbia estuary during the study period

Parameters		Autumn			Winter			Spring			Summer		
		GPP	NPP	R	GPP	NPP	R	GPP	NPP	R	GPP	NPP	R
Air temperature	r	-0.09	-0.11	0.07	-0.22	-0.46	0.62	0.14	0.16	0.12	-0.49	**-0.79**	0.36
	PE	0.27	0.27	0.27	0.20	0.17	0.13	0.27	0.27	0.27	0.18	**0.09**	0.21
	r/PE	-0.33	-0.42	0.26	-1.06	-2.74	4.76	0.52	0.59	0.43	-2.69	**-8.58**	1.72
Water temperature	r	-0.58	-0.62	-0.01	-0.07	-0.14	0.19	-0.41	-0.38	-0.44	-0.07	0.05	-0.20
	PE	0.18	0.17	0.28	0.21	0.21	0.21	0.23	0.24	0.22	0.24	0.24	0.23
	r/PE	-3.15	-3.67	-0.04	-0.32	-0.68	0.92	-1.81	-1.60	-2.00	-0.29	0.22	-0.89
Secchi depth	r	-0.51	-0.56	0.04	-0.51	-0.39	-0.24	0.39	0.44	0.33	-0.64	-0.56	-0.25
	PE	0.20	0.19	0.28	0.16	0.18	0.20	0.23	0.22	0.25	0.14	0.16	0.22
	r/PE	-2.54	-2.98	0.13	-3.21	-2.13	-1.19	1.69	1.99	1.34	-4.50	-3.42	-1.12
Salinity	r	0.08	0.13	-0.20	**-0.74**	**-0.77**	0.16	0.25	0.27	0.23	-0.31	-0.08	-0.42
	PE	0.27	0.27	0.26	**0.10**	**0.09**	0.21	0.26	0.26	0.26	0.22	0.24	0.20
	r/PE	0.28	0.46	-0.76	**-7.63**	**-8.82**	0.75	0.97	1.04	0.86	-1.43	-0.33	-2.13
Conductivity	r	0.09	0.14	-0.21	**-0.74**	**-0.76**	0.12	0.32	0.33	0.29	-0.28	-0.11	-0.33
	PE	0.27	0.27	0.26	**0.10**	**0.09**	0.21	0.25	0.25	0.25	0.22	0.24	0.21
	r/PE	0.33	0.53	-0.79	**-7.78**	**-8.39**	0.58	1.27	1.33	1.17	-1.28	-0.46	-1.54
pH	r	0.36	0.44	-0.25	0.29	0.15	0.31	0.13	0.18	0.06	0.50	0.17	0.62
	PE	0.24	0.22	0.26	0.20	0.21	0.19	0.27	0.27	0.27	0.18	0.23	0.15
	r/PE	1.51	1.99	-0.96	1.49	0.72	1.61	0.46	0.68	0.22	2.79	0.71	4.24
Chlorophyll-a	r	0.37	0.36	0.15	0.31	0.08	0.55	0.01	-0.06	0.09	0.56	0.21	0.65
	PE	0.24	0.24	0.27	0.19	0.21	0.15	0.28	0.27	0.27	0.16	0.23	0.14
	r/PE	1.53	1.52	0.54	1.63	0.36	3.66	0.04	-0.21	0.33	3.40	0.92	4.79
Phaeopigments	r	0.66	0.74	-0.15	0.66	**0.75**	-0.30	0.08	0.01	0.17	**0.72**	0.49	0.51
	PE	0.16	0.12	0.27	0.12	**0.09**	0.19	0.27	0.28	0.27	**0.12**	0.18	0.18
	r/PE	4.18	5.91	-0.54	5.46	**8.00**	-1.51	0.30	0.02	0.63	**6.21**	2.69	2.84
Dissolved oxygen	r	0.45	0.54	-0.24	0.09	-0.15	0.57	0.35	0.35	0.33	0.50	0.00	**0.88**
	PE	0.22	0.20	0.26	0.21	0.21	0.14	0.24	0.24	0.25	0.18	0.24	**0.05**
	r/PE	2.06	2.75	-0.92	0.40	-0.73	4.01	1.42	1.47	1.33	2.80	-0.01	**16.96**

water temperature values varied within a range of 10.5 °C to 15.1 °C during the wet period and 15 °C to 24.5 °C during the dry period due to the large difference in altitude along the Oum Er Rbia River, the geographical characteristics of each station and the sampling period (Benamar et al., 2019). In the Bouregreg estuary, mean annual temperature values of 16.7 °C to 17.9 °C were noted by Cherkaoui et al (2003) while other measurements revealed temperatures ranging from 17.0 °C to 17.8 °C and increasing as one moves upstream due to the discharge of warm water from Wadi Akrech (Zerki et al., 2011). Other observations revealed near-surface temperatures between 18.7 °C and 22.5 °C (Geawhari et al., 2014) and between 25 °C and 26 °C (Fathi et al., 2021) in the Oued Loukkos estuary. In the Oued Sous estuary, monthly temperature values ranging between 19 °C and 25 °C were recorded by Ait Alla et al., (2006) while in the Oued Sebou estuary, water temperature varied between 16.6 °C and 27.5 °C (Kaioua et al., 2022).

Suspended matter concentrations recorded in the Oum Er Rbia estuary ranged from 14.92 mg/L to 51.60 mg/L (Cheggour et al., 2000) and turbidity values in river water samples ranged from 0.43 NTU to 46.9 NTU (Nephelometric Turbidity Units) during the dry period and from 1.24 NTU to 182 NTU during the rainy season (Benamar et al., 2019). In the Bouregreg estuary, mean annual turbidity values ranging from 4.6 NTU to 15.3 NTU were observed (Cherkaoui et al., 2003), and suspended solids were as low as 26.8 mg/L and 24.5 mg/L during the spring and neap tides,

Table 3. Two-way analysis of variance ANOVA (station x season) of gross primary production (GPP), net primary production (NPP) and respiration (R)

Source		Degree of freedom	Sum of squares	Mean square	F value	Pr (>F)
GPP	Station	1	2128	2128	0.307	0.585
	Season	3	37393	12464	1.796	0.177
	Station: Season	3	16486	5495	0.792	0.511
	Residuals	22	152670	6940		
NPP	Station	1	46	46.3	0.017	0.898
	Season	3	7907	2635.8	0.964	0.427
	Station: Season	3	6937	2312.5	0.846	0.483
	Residuals	22	60122	2732.8		
R	Station	1	2227	2227	1.147	0.2959
	Season	3	19840	6613	3.405	**0.0356 ***
	Station: Season	3	4862	1621	0.835	0.4892
	Residuals	22	42725	1942		
Signification codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

respectively, at the mouth, while they were 98.5 mg/L and 95.3 mg/L upstream of the river (Priya et al., 2022). The concentration of suspended solids in the Sebou estuary varies between 187 mg/L and 521 mg/L, with the lowest value observed in summer and the highest in spring (Kaioua et al., 2022). In the Bouregreg estuary, Haddout (2020) noted that salinity along the estuary varies between 35 ‰ at the mouth and 0.5 ‰ at the limit of the saline intrusion zone and that the length of the saline intrusion is about 20 km, while Priya et al., (2022) reported that the maximum and minimum salinity values vary according to stations, tidal variations and seasons and gradually decrease from the mouth to upstream during high water and low water of both tides with values between 35 g/L and 20 g/L during high spring tide; 33.7 g/L and 12.4 g/L during low spring tide; 33.7 g/L and 11.4 g/L during high neap tide; and 32.7 g/L and 7.7 g/L during low neap tide. Other authors have reported salinity fluctuations of between 22.12 g/L and 34.40 g/L in the Oum Er Rbia estuary (Cheggour et al., 2000), between 0.7 psu and 36.2 psu (Practical Salinity Units) in the Loukkos estuary (Geawhari et al., 2014), from 31 g/L to 36.8 g/L in the Oued Laou estuary (Rijal Leblad et al., 2020) and from 1815 mg/L to 9502 mg/L in the Sebou estuary (Kaioua et al., 2022). The conductivity values observed in the estuary during this study are similar to those found in other estuaries: At high tide, mean conductivity values in the Loukkos estuary fluctuate from 0.79 mS/cm to 52.70 mS/cm, while at low tide, mean values fluctuate from 2.97 mS/cm to 33.62 mS/cm (El Morhit et al., 2012) and appear to follow an increasing gradient from upstream to downstream, with a minimum of 0.5 mS/cm and a maximum of 69.75 mS/cm (Fathi et al., 2021). Along the Bouregreg estuary, the average electrical conductivity values recorded show a decreasing gradient from downstream to upstream ranging from 4870 µS/cm to 451 µS/cm (Zerki et al., 2011) and from 27 mS/cm to 7.90 mS/cm (El Harim et al., 2021) due to the distance from marine influences and dilution by freshwater inputs. Other observations recorded electrical conductivity values ranging from 53.23 µS/cm to 57.24 µS/cm (Chahouri et al., 2022) and from 2836 µS/cm to 14847 µS/cm, with the highest values in autumn and the lowest in spring (Kaioua et al., 2022) in the Oued Sous and Oued Sebou estuaries respectively. The pH of the waters of the Oum Er Rbia River varies from 7.56 to 8.59 during the dry period and from 7.42 to 8.53 during the rainy season.These values indicate that the water samples from this river have alkaline properties (Benamar et al., 2019). In contrast, in the Oum Er Rbia estuary, a wider range of pH in the water column fluctuating between 6.74 and 9.19 and varying from slightly acidic to highly alkaline reveals a wide variability in environmental conditions (Bengriche et al., 2024). In the Oued Laou estuary, Rijal Leblad et al. (2020) measured pH values fluctuating between 7.78–8.24 in spring, 7.81–8.21 in summer, 7.82–8.11 in autumn and 7.80–8.01 in winter.) In the Bouregreg estuary, a study of the spatial evolution of pH shows the existence of a spatial variation characterised by the presence of two zones, one upstream and the other downstream. The upstream zone is characterised by relatively high pH values of between 7.6 and 9.6, while the downstream zone is characterised by a very low variation in pH ranging from 7.00 to 7.70 (Zerki et al., 2011) with mean annual values ranging from 7.32 to 8.40 (Cherkaoui et al., 2003). In the Oued Sous estuary, monthly pH values are relatively constant, ranging from 6.8 to 8.2 (Ait Alla et al., 2006).

The dissolved oxygen concentrations found in the estuary during this study show similarities with those documented in other estuaries. In the Bouregreg estuary, the range of dissolved oxygen concentrations indicates a healthy water mass for estuarine biota in all depth profiles with variations from 5.5 mg/L to 11.8 mg/L at both tides (Haddout et al., 2022). In the Loukkos estuary, the values reported by El Morhit et al., (2013) vary between 6 mg/L and 9 mg/L with an average of 8.68 mg/L, while Fathi et al., (2021) noted an almost constant dissolved oxygen level fluctuating around 6 mg/L. Similar studies have revealed dissolved oxygen levels ranging from 5.00 mg/L to 8.90 mg/L in the Oum Er Rbia estuary (Cheggour et al., 2000), from 2.31 mg/L (downstream of the mouth with a predominance of marine waters) to 7.5 mg/L (upstream of the estuary receiving only freshwater) for the Oued Sebou (Loukili and Belghyti, 2007) and from 6.17 mg/L to 7.9 mg/L for the Oued Sous estuary (Chahouri et al., 2022). Apart from the high concentrations recorded in March 2019 at station S1, which are due to the blooming of the dinoflagellate *Prorocentrum micans* responsible for the large-scale red water phenomenon (Bengriche et al., 2023), the chlorophyll-a and phaeopigment values observed in the estuary during this study are similar to those reported in other estuaries. In the Bahía Blanca estuary in Argentina, Carbone et al. (2016) reported that the highest chlorophyll-a concentrations ranged from 1.87 to 13.7 mg/m3 and were recorded near wastewater, while the seasonal distribution of the phaeopigment showed an inverse trend of chlorophyll-a, mainly in areas where the influence of the adjacent sea is strongest, with two significant peaks reported, in winter and spring (7.65 µg/L and 7.96 µg/L, respectively), which coincide with the decrease in chlorophyll-a values. Fernández et al. (2021) reported that the highest annual mean concentrations of chlorophyll-a and phaeopigments were recorded in September (30.68 ± 11.21 and 19.13 ± 8.88 µg/g dry matter for chlorophyll-a and phaeopigments, respectively) and August (9.801 ± 2.96 and 8.16 ± 0. 81 µg/g dry matter), while the lowest concentration of chlorophyll-a was recorded in February (1.25 ± 0.41 µg/g dry matter) and January (1.25 ± 0.56 µg/g dry matter) and the lowest concentration of phaeopigments was recorded in May (3.01 ± 0.86 µg/g dry matter) and April (2.86 ± 0.19 µg/g dry matter). In the Gironde estuary, chlorophyll-a values ranged from around 4 to 8 µg/L, while phaeopigments ranged from around 2 to 10 µg/L (Abdou et al., 2020). In the Seine River in France, sediment concentrations of chlorophyll-a and phaeopigments were highest in freshwater mudflat sediments, reaching values between 21–124 µg/g and 253–611 µg/g dry matter respectively, with peaks in March for chlorophyll-a and in June for phaeopigments. In contrast, the lowest levels (3.3–8.5 µg/g for chlorophyll-a and 13–48 µg/g for phaeopigments) were observed in the sediments of the riparian wetland, while the sediments of the brackish mudflat showed respective concentrations of 6.3–63 µg/g for chlorophyll-a and 5.3–80 µg/g for phaeopigments (Laverman et al., 2021). As for the temporal differences between the study stations, Fernández et al. (2021) reported differences in the concentration of chlorophyll-a and phaeopigments at the sampling sites, with a tendency to show the highest values in winter and spring.

Primary production in rivers and aquatic ecosystems is influenced by various environmental and biological factors, such as the availability of sunlight for photosynthesis (Bordin et al., 2023; Horemans et al., 2020; Meng et al., 2023; Shen et al., 2015; Villafañe et al., 2015), nutrients (Hong et al., 2022; Li et al., 2023; Zhang et al., 2022), water temperature (Hong et al., 2022; Li et al., 2023; Meng et al., 2023; Shen et al., 2015; Zhang et al., 2022), water turbidity (Drylie et al., 2018; Li et al., 2023; Shen et al., 2015, 2019), seasonal variations (Hong et al., 2022; Li et al., 2023), aquatic vegetation and phytoplankton (Bordin et al., 2023; Li et al., 2023), water pollution levels (Menció et al., 2023), water flow (Bordin et al., 2023). The combination of these and other factors can vary according to the type of aquatic ecosystem (river, lake, estuary, marsh, etc.) and its geographical location, making the regulation of primary production complex and variable from one ecosystem to another.

The results obtained in this research showed values ranging from 9.28 to 467.07 mg C/m3/h for gross primary production (GPP), from 3.09 to 248.13 mg C/m^3/h for net primary production (NPP) and from 4.03 to 262.73 mg C/m3/h for respiration (R), which are comparable to other estuarine systems. In Indonesia, Nurfadillah et al. (2021) found that in the Kuala Gigieng estuary, net primary productivity (NPP) and gross primary productivity (GPP) ranged from 3.47 to 27.77 mg C/m^3/hour and from 5.20 to 32.98 mg C/m^3/hour respectively, while Faris et al. (2022) noted that productivity values in the waters of the southern estuary of Dhi Qar province in Iraq ranged from 38.99 to 130.05 mg C/m3/hour, with two peaks in autumn and spring. In Iraqi marsh systems, mean phytoplankton primary productivity values ranged from 11.71 to 249.79 mg C/m^3/h for surface water samples, while for 1m depth they ranged from 3.75 to 123.44 mg C/m^3/h (Hassan et al., 2011) and from 1.6 to 407 mg C/m^3/hour depending on the station (Maulood and Hassan 2021). The significant positive correlations between chlorophyll pigments and GPP in summer and NPP in winter and between Respiration and dissolved oxygen in summer are in agreement with the findings of several authors: Utami and Mahardika (2019) showed that chlorophyll-a and nitrogen nutrients were the main factors impacting spatio-temporal variations in phytoplankton primary productivity in shrimp ponds. Stepwise multiple regression analysis showed that phytoplankton primary productivity is mainly influenced by chlorophyll-a, water temperature, pH, suspended solids and nitrite, while total productivity can be predicted by conductivity, water temperature and dissolved oxygen (Li et al., 2023). Furthermore, Bordin et al. (2023) reported that the most relevant driving forces for GPP are nitrate, salinity, chlorophyll-a, wind speed and direction, water flow, silicate and turbidity, while the main driving mechanisms for Respiration are photosynthetically active radiation, temperature, wind speed, chlorophyll-a, turbidity and nitrate.

The significant negative correlations observed between GPP with conductivity and salinity in winter and between NPP with conductivity, salinity and air temperature in winter and summer are consistent with the observations of many researchers. Sukla et al. (2013) noted that during post-monsoon, GPP and NPP showed significant negative correlations with water temperature and significant positive correlations with Secchi transparency. Furthermore, Chaudhuri et al. (2012) found that high aquatic turbidity, conductivity and suspended particles were limiting factors that attenuated light penetration and had a negative influence on primary production.

CONCLUSION

Primary production in the Oum Er Rbia estuary shows disparities both in time and space. The highest levels of production are observed during the spring season (station S2), while the lowest levels are recorded during the summer season (station S1). The spatial variation in productivity can be attributed to differences in the environmental conditions specific to each study station, which include variations in water temperature, salinity, depth of light penetration, and other factors that directly influence the growth of chlorophyll organisms. At the same time, seasonal variations in productivity can be due to changes in meteorological and environmental conditions throughout the year. For example, variations in air and water temperature, seasonal nutrient inputs and the availability of sunlight can influence primary production.

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