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Relationship of salinity, temperature, pH, and transparency to dissolved oxygen in the Bouregreg estuary (Morocco): First results

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ABSTRACT

Dissolved oxygen (DO) concentration is an essential indicator for assessment of estuary ecosystems. According to our knowledge, there is no research on the depth profiles of the DO and associated water quality variables of the entire Bouregreg estuary (Morocco). Water samples were collected from three stations at 0.5-m depth intervals during high and low tides (10/11/2021, 20/03/2022, and 02/07/2022). Our study shows that the DO concentrations ranged between 5.5 and 11.8 mg/L and demonstrated an inconsistent stratification pattern. When the tide was high and low in most of the study area, the bottom layer had a higher concentration of DO than the surface layer. There was a relatively high concentration of DO in the bottom layer of the estuary and a relatively low concentration in the surface layer of the estuary due to a high rate of freshwater flow on the surface (the release of Sidi Mohammed Ben Abdellah dam and the existence of estuarine gravitational circulation). Salinity, pH, water temperature, and water transparency ranged from 19.4 to 35.8 ppt, 7.0 to 8.7, 17 to 23 °C, and 16 to 21 cm, respectively, considering the depth profiles in the study area. The study provides scientific support for ecology operation and considerable advances in understanding the ecosystem dynamics of the Bouregreg estuary.

Key words: Bouregreg estuary, dissolved oxygen, Morocco, stratification

HIGHLIGHTS

- Depth profiles of the DO and associated water quality variables are studied.
- The result shows that the DO concentrations ranged between 5.5 and 11.8 mg/L and demonstrated an inconsistent stratification pattern.
- The study provides scientific support for ecology operation and considerable advances in understanding the ecosystem dynamics of the Bouregreg estuary.

INTRODUCTION

Many definitions and classifications have been proposed for estuaries, which mostly depend on their application (Pritchard 1967; Hume & Herdendorf 1988; Davidson & Council 1991; Savenije 2006). In most cases, estuaries were defined based on the relative influence of tides, waves, rivers, sediment types, sediment supply, vegetation, geology, or time (Savenije 2006, 2005). Additionally, estuaries play an essential role in the human–earth system, affecting freshwater resources, the mixing between the ocean and river water, and the health of aquatic ecosystems (Savenije 2015; Wei *et al.* 2017). This makes the functioning of estuarine systems an important field of research. The dissolved oxygen (DO) concentration in a river is an essential indicator of ecosystem assessment. DO decrease in rivers impacts biological activities and results in reductions in benthic animal populations (Bu *et al.* 2021). A low DO concentration may slow the degradation of pollution, weaken the capacity of water's self-purification, and even decrease the quality of the aquatic ecosystem. In recent decades, hypoxia (DO $<$ 2 mg/L) has been frequently reported, which is an urgent warning for river ecosystem health (Ji *et al.* 2017). DO is required for respiration by most aquatic biota. Apart from this, DO combines with other important elements such as carbon, sulphur, nitrogen and phosphorus that could have been toxicants in the absence of oxygen in the water bodies to form carbonate, sulphate, nitrate, and phosphate, respectively, contributing, in this way, to the required compounds for the survival of aquatic organisms (Rouf *et al.* 2022). Therefore, natural stream purification processes require adequate oxygen levels in order to provide aerobic life forms. As DO levels in water drop below 5.0 mg/L, aquatic life is put under physiological stress (Rouf *et al.* 2022). Oxygen levels that remain below 1–2 mg/L for a few hours can adversely affect the growth and survivability of aquatic organisms. DO is, therefore, an indispensable element to all forms of aquatic life (Sarker *et al.* 2021). DO generally varies horizontally along the course of the waterway in shallow rivers but is most likely to vary vertically in the water column in deep rivers. A theoretical deduction shows that vertical stratification of DO concentration can be explained by the extended Hansen and Rattray's central region theory, which suggest that vertical DO profiles are mainly controlled by biological factors such as photosynthesis, biochemical oxygen demand (BOD), sediment oxygen demand (SOD), and physical factors such as surface re-aeration, river flow, and estuarine gravitational circulation (Lin *et al.* 2006). Freshwater from inland and saline water from the sea can generate a stratified layer and limit the DO in the epilimnion and the hypolimnion region (Rouf *et al.* 2022). Alternately, a deep river can also generate an unstratified water column due to the mixing of water. The stratification pattern of DO in estuaries is considered a highly informative variable for obtaining the ecosystem's functionality and behaviors. Stratification of DO has been reported from various estuaries of the world in recent years (e.g., Lin *et al.* 2006; Liblik *et al.* 2020; Rouf *et al.* 2022). It appears that vertical distributions of DO concentrations in estuaries are affected by different parameters in different systems. The dominant parameters in a system should be unknown a priori. Most of the studies regarding the Bouregreg estuary are focused on pollution assessment (Cherkaoui *et al.* 2005; El Harim *et al.* 2019), salt-intrusion (Haddout *et al.* 2020, 2021), distribution of water quality variables (El Amraoui *et al.* 2015), sediment/ heavy metal studies (Priya *et al.* 2018, 2021, 2022). All these studies were based on surface layer observation instead of considering the vertical profile of the river. Thus, an analysis of the vertical profile of DO and its stratification, in the Bouregreg estuary is needed that helps in improving. The understanding of the river ecosystem, which is beneficial for estuarine ecologists and coastal managers.

MATERIALS AND METHODS

Study area

The Bouregreg River is located in northwestern part of Morocco, stretching about 240 km from its source in the Middle Atlas Mountains to the Atlantic Ocean. It belongs to a watershed covering an area of approximately 9,800 km^2 with elevation ranging from 0 to 1,627 m (Zellou & Rahali 2017). The climate is semi-arid with an average annual rainfall of 440 mm and an average annual temperature of 18 °C. The Bouregreg estuary is located on the Atlantic coast between the two cities Rabat and Sale 34°N and 6°50′W (Figure 1). It has a length of 23 km, limited by the Sidi Mohammed Ben Abdellah dam and an average width of 150 m. Its average freshwater flow varied from 3 to 84 m^3s^{-1}. Additionally, the tide near the estuary mouth is mainly semi-diurnal with a 12.25-h tidal cycle and is a meso-/micro-tidal estuary with an average tidal range of only 2.3 m. The absence of a real fluvial flow, following the disappearance of flooding events, clearly influences the estuary's functioning, where the hydrodynamics are governed by the tides (their height varies from 0.5 to 3.3 m) (Cheggour *et al.* 2005). Tidal excursions, i.e., the distance that a water particle travels between low tide and high tide ranges between 3.5 and 7 km. The channel width is about 150–140 m to 57 m and the average depth ∼3.5–7 m, approximately. This estuary is dominated by seawater, with a minimal influx of freshwater for most of the year. Near the mouth, there are agricultural and industrial areas. Some urban sewage from Rabat and Sale is directly discharged into the estuary.

On the other hand, the physical–chemical structure of the Bouregreg estuary is characterized by two gradients: one is the increment of particulate organic matter and nutrients and another is the enrichment of salts, the latter playing therein a more important role. The estuarine waters, due to oceanic influence, show a double thermal gradient horizontally with the season. In fact, their temperature decreases of the upstream towards the downstream during the dry period than the wet period. The saltwater intrusion of the estuary was found to increase with time since the construction of the Sidi Mohammed Ben Abdellah dam. The waters, in general, are well oxygenated and rich in suspended particulate matters. High concentrations of nutrients occur at midstream and upstream parts. In addition, Figure 2 gives the longitudinal evolution of measured river width, cross-sectional area, and depth elaborated with an intensive field survey.

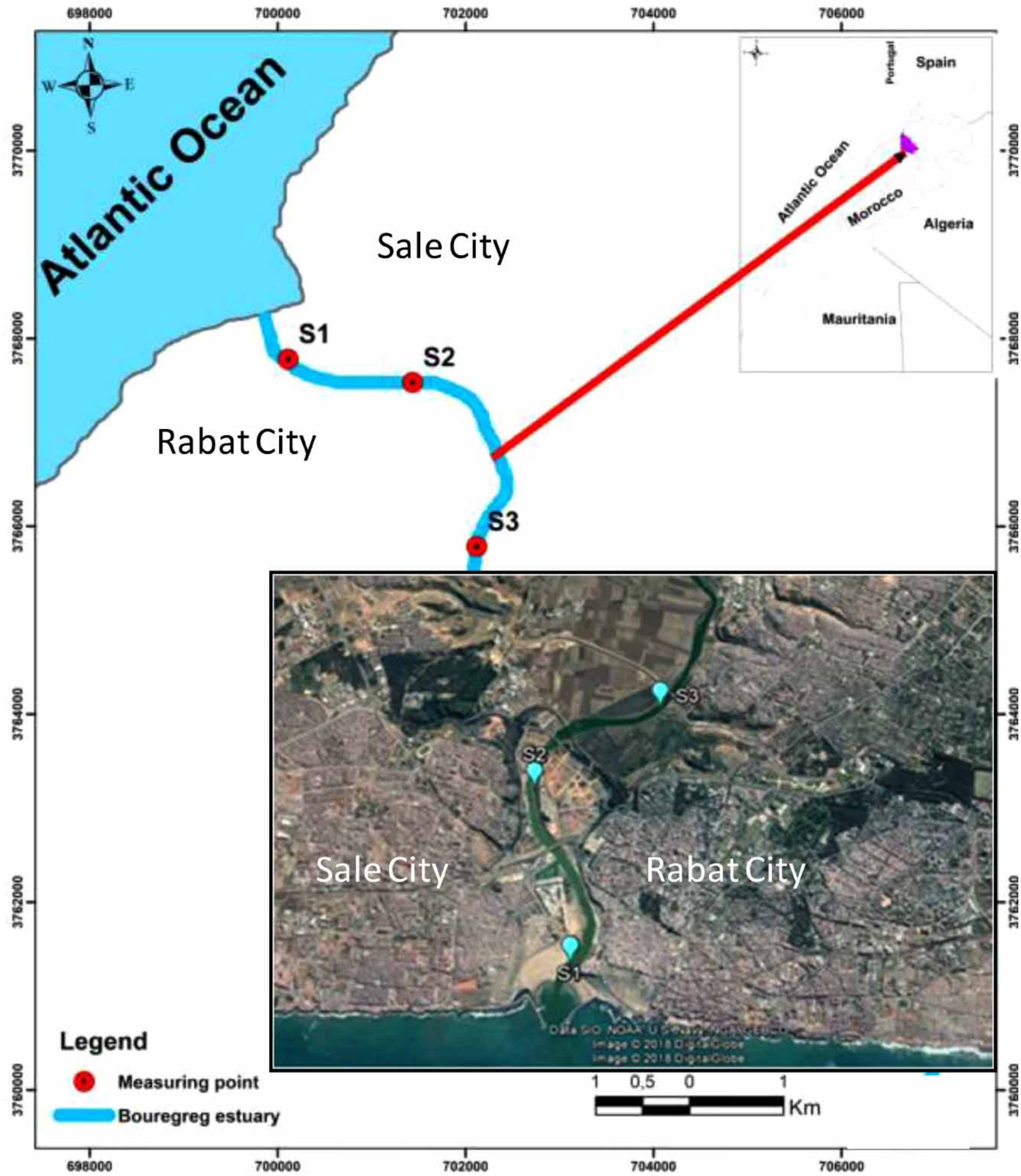

Figure 1 | Map showing the Bouregreg estuary and location of measuring stations.

Data observation and preparation

Water samples were collected on the following days, months, and years, 10/11/2021; 20/03/2022; and 02/07/2022 at the stations indicated in Figure 1, for *in situ* measurements and laboratory analysis (study desk). Sampling was conducted during the slack period of both high tide and low tide. Water sampling date, tidal conditions, weather, and atmospheric temperature are given in Table 1. Water samples were collected by using a bottom water sampler in 0.5 m of depth intervals. During *in situ* measurements, salinity, water temperature, and pH were measured by YSI Pro30 conductivity meter attached to a 10-m cable. Also, a Global Positioning System (GPS) was used to record the positions of every measurement. The equipments used are adequate to carry out various measurements in cost-effective way. The measurements started from the mouth moving upstream, keeping pace with the tidal wave. The processed water samples were taken to the study desk at Casablanca (Morocco)

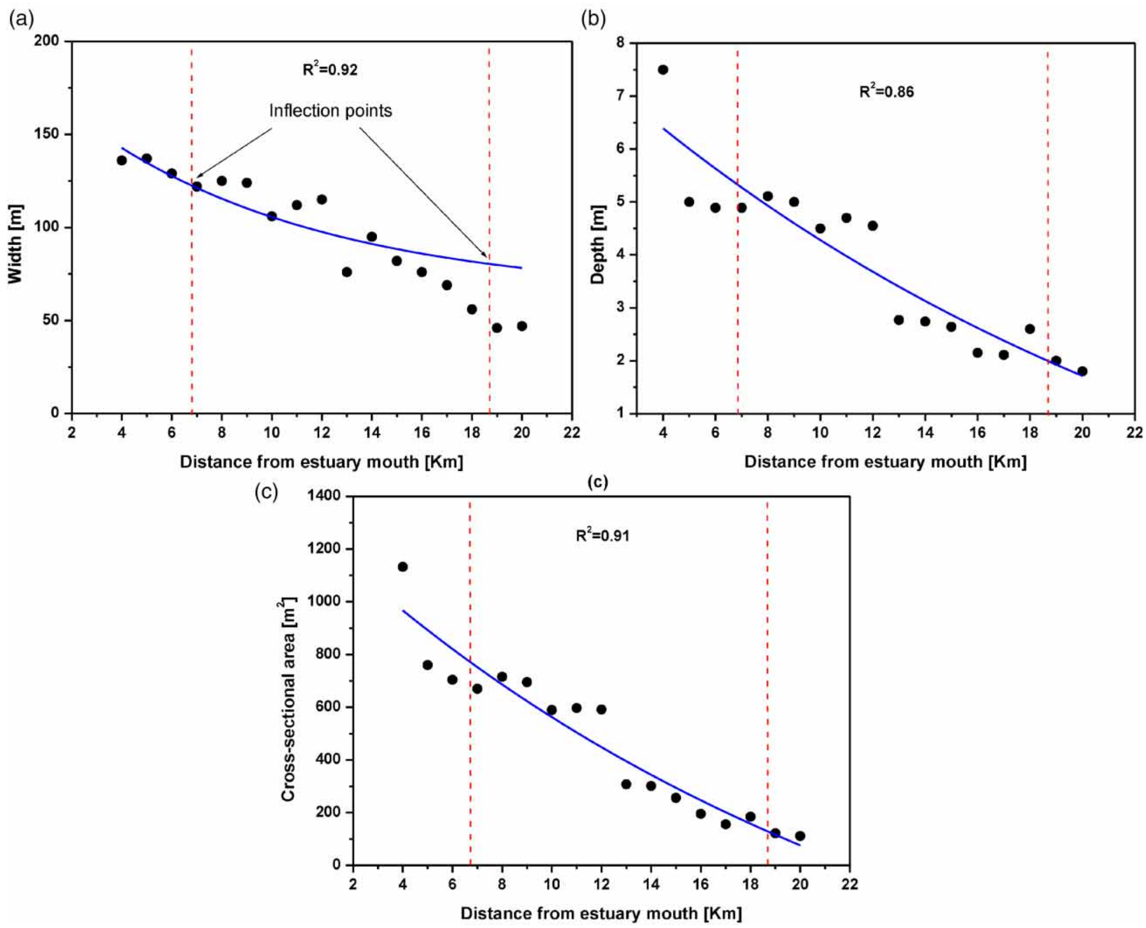

Figure 2 | River width, cross-sectional area, and depth characteristics of the Bouregreg estuary.

Table 1 | Station-wise water sampling date with their respective, tidal level, weather, and atmospheric temperature

Station	Sampling date	Tide conditions	Weather and atmospheric temperature
Station 1 at 1 km from the mouth	10/11/2021	HW	Cloudy
		LW	Cloudy
	20/03/2022	HW	Cloudy
		LW	Sunny
	02/07/2022	HW	Sunny
		LW	Sunny
Station 2 at 4 km from the mouth	10/11/2021	HW	Cloudy
		LW	Cloudy
	20/03/2022	HW	Cloudy
		LW	Sunny
	02/07/2022	HW	Sunny
		LW	Sunny
Station 3 at 7 km from the mouth	10/11/2021	HW	Cloudy
		LW	Cloudy
	20/03/2022	HW	Cloudy
		LW	Sunny
	02/07/2022	HW	Sunny
		LW	Sunny

HW = high water; LW = low water.

for analysis using the Winklers method (APHA, AWWA & WEF 1995) was applied for the determination of DO. An accuracy of 0.1% was observed while comparing with the standard-based dissolving known quantities of O_2 in O_2-free water. Mann–Whitney test was conducted at a 5% significance level in order to determine the statistical difference between the surface and bottom layers of the DO of each depth profile. To calculate the percentage saturation of DO, a monogram was used to get a quick approximate oxygen saturation value (Behar *et al.* 1996).

RESULTS AND DISCUSSION

DO stratification

The depth profiles of DO in three stations during high and low tides during 10/11/2021; 20/03/2022; and 02/07/2022 are shown in Figure 3. DO concentrations ranged from 5.5 to11.8 mg/L at both tides during the sampling

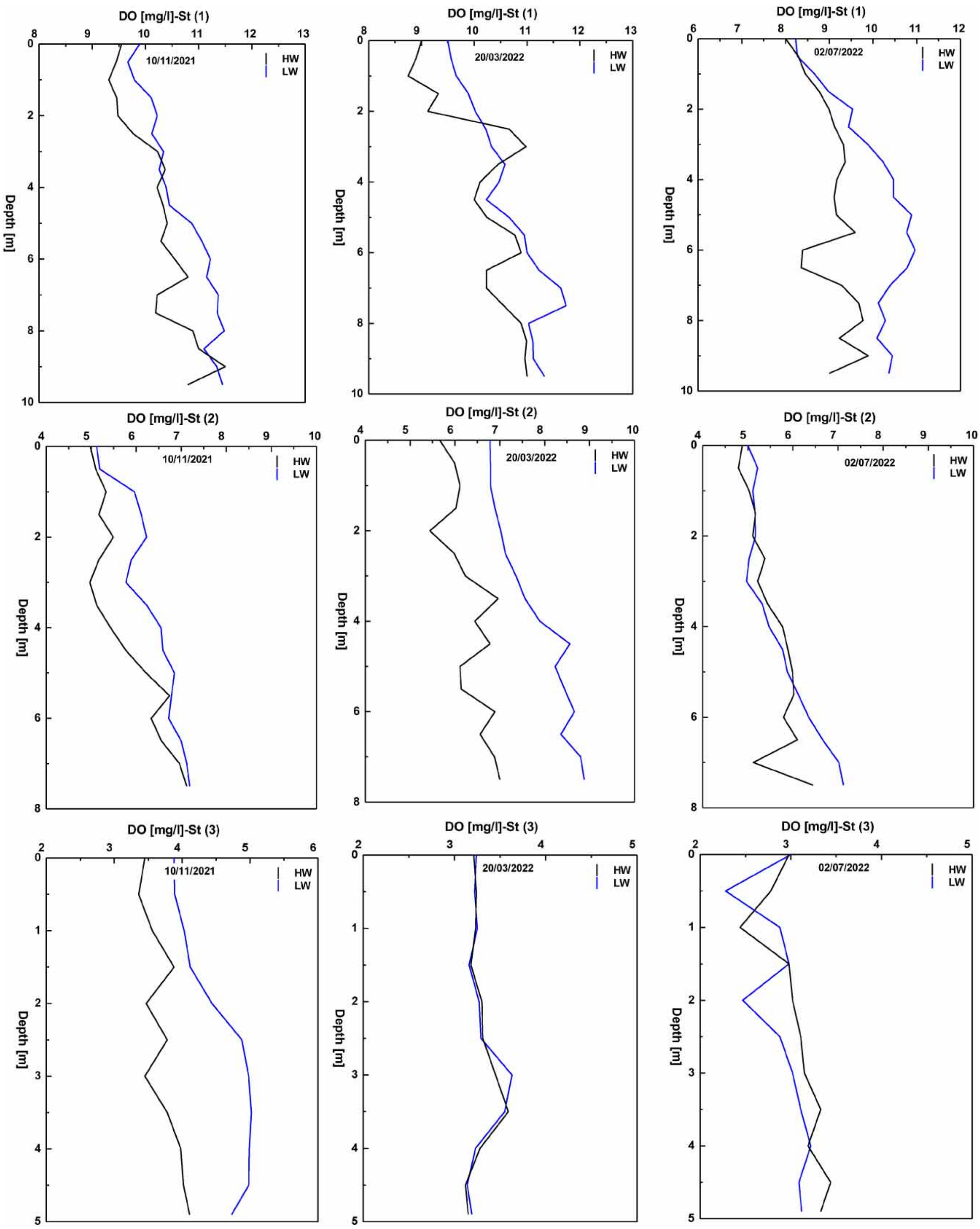

Figure 3 | DO profiles during high and low tides in three months in Stations 1–3.

months throughout the depth profiles. The range of DO in the stations indicates a healthy water mass for estuarine biota throughout the profiles. EL Harim *et al.* 2021 recorded the DO as 3.37 mg/L at 7 km to 9.57 mg/L at the mouth (during the autumn period) and from 2.93 mg/L at 7 km to 9 mg/L at the mouth (during the summer period) at around 0.2 m depth for the samples obtained from the lower stream of the Bouregreg estuary. During the cold period, heavy rainfall increases the exchange of oxygen with the atmosphere and facilitates the entry of air into the water bodies of this estuary and therefore a dilution of the polluting load. Furthermore, lower temperatures favour the dissolution of oxygen thereby enhancing the DO concentrations. The lowest concentrations of DO are recorded in station 3 where strong anthropogenic pressure is experienced by solid waste, air pollution, the action of microorganisms (depleting the oxygen medium by degrading the abundant organic matter in this station), but especially by the warming of the water of this station by discharges of raw sewage rich in fermentable organic matter, which are liable to be oxidized causing a decrease in the dissolution of oxygen (Brahimi & Chafi 2014). The DO results in the present work are still higher than those recorded in this estuary before the development works of the Bouregreg valley (from 1.5 to 5.5 mg/L) (Cherkaoui 2006). According to the Moroccan classification of surface waters, the waters of this estuary are classified from average to good quality. On the other hand, higher DO values were found in the low tide than that of the high tide in most of the profiles due to strong tidal mixing in the estuary, with cold incoming seawater and warm outgoing freshwater. During the low tide, the salinity values are lower than that during the high tide. DO values are relatively lower in high saline waters as the mass transfer of atmospheric oxygen is reduced in ionic water thereby causing a decrease in the dissolution of oxygen in saline water. It was noticed during the sampling that the water current was relatively strong during the low tide than that of the high tide in stations 1 and 2. Higher turbulence enhances the surface area and increases the dissolution of oxygen; so, it is suspected that this phenomenon also influences the DO variation in the observation sites. Supporting this, Pereira *et al.* 2013 also reported that intense water–atmosphere interactions and photosynthetic activity dominated the concentration of DO in the Amazon Coast. Small depth may also be responsible for mixing or little stratification in the study area. DO was found relatively higher in November and March than July due to the autumn and spring seasons. Maximum three units (mg/L) of variation in DO were noticed in the depth profiles of the stations. It is noticeable that the DO concentration was relatively high in the bottom layer and low in the surface layer during both the high and low tides in most of the months. This may be associated with the temperature variations; bottom cool layers exhibiting higher DO than warm top layers. The obtained results from Mann–Whitney test suggest that both significant difference ($P < 0.05$) and no difference ($P > 0.05$) between the surface and bottom layer DO profiles were evident in the study area. Therefore, it can be said that the stratification of DO was inconsistent in the depth profiles of study area. Lin *et al.* 2006 found similar stratification pattern in the Cape Fear River Estuary of North Carolina due to higher estuarine gravitational circulation; and same results are investigated by Rouf *et al.* 2022 in the Pasur-Rupsha estuary of Bangladesh. In contrast, Liblik *et al.* 2020 reported strong stratification of DO due to wind forcing circulation patterns, upwelling and downwelling in the Changjiang (Yangtze) Estuary, China.

Relationship of DO profiles with salinity, temperature, pH, and water transparency

Depth profiles of DO, salinity, temperature, and pH during the high and low tides in 3 sampling months in the study area are shown in Figure 4 (DO from Figure 3). The vertical profiles of DO, temperature, salinity, and pH showed an inconsistent stratification pattern throughout the study period.

Temperature controls the lives of aquatic organisms (Hauer & Hill 2007). The temperature of a particular water system usually affects the solubility of substances on it. Certain substances dissolved significantly in water at high temperatures, others do so at low temperature (Averill & Eldredge 2012; Rouf *et al.* 2022). Temperature has direct relation with sedimentation and filtration rate as well as with the metabolism rate of aquatic organisms. The water temperature of the Bouregreg estuary varies according to the seasons and the nature of the waters that are salted downstream and freshwater upstream. The average water temperature in the surface of this estuary oscillates between 19.98 and 21.80 °C (EL Harim *et al.* 2021). The temperature rise in the upstream sector can be explained by the direct influence of the air temperature, given the shallow depth of the water layer upstream of the16-km stretch (EL Harim *et al.* 2021). During the study period, water temperature varied from 17 to 23 °C in the vertical profiles of the stations. One or less than one unit (°C) variation in temperature was noticed during study period. Less variation (<2 units) of temperature within the profiles indicates a weak stratification, which addresses a level of water mixing. This mixing is thought to be regulated mostly by the water movement following ebb and flood tides in the estuary. The relation between the temperature and DO was found inversely correlated (−0.252) with

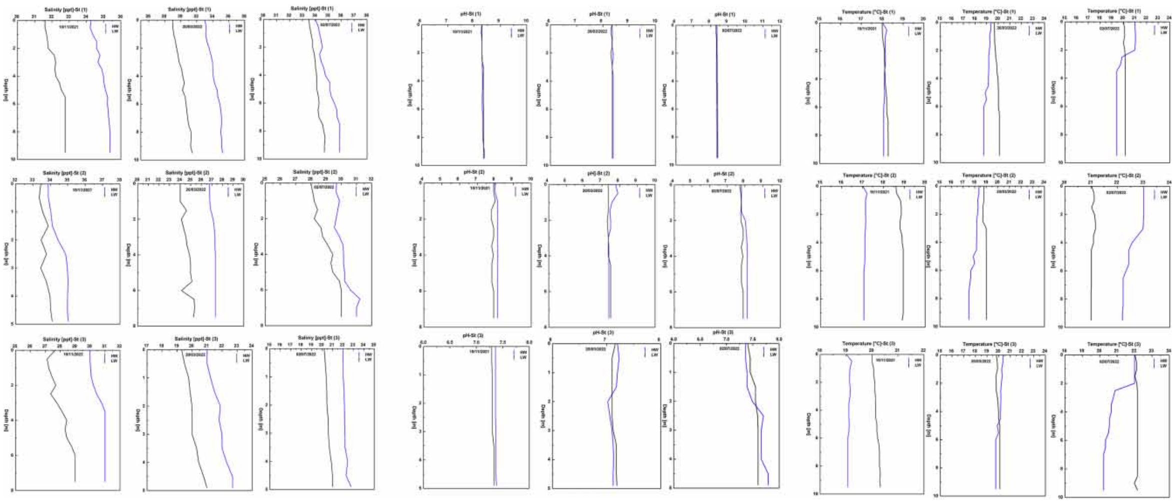

Figure 4 | Salinity, pH, and temperature with depth profiles during high and low tides in 3 sampling months in Stations 1–3.

high significance level ($P < 0.000$). Some temperature profiles showed inverse relation with DO profiles while others showed opposite or no relation. Seasonal variation of temperature within the temperature profile was found responsible factor for that minimum level of inverse correlation coefficient.

Water salinity in the stations ranged from 19.4 to 35.8 parts per thousand (ppt) during the study period. Maximum one unit (ppt) variations in salinity were noticed in all profiles. Relatively low variations observed in those stations are located downstream. The salinity profiles, however, indicate a weak stratified profile in the stations. Variation in salinity profiles from the high tide to low tide, shown in Figure 4, addressed that the water movement is regulated by ebb and flood tides along with the differences in the density of water. The movement of water due to the density differences in turn expresses the existence of estuarine gravitational circulation. These regulatory mechanisms may be responsible for the weak stratification in the estuary. These results are comparable to those recorded in the same estuary by Haddout *et al.* (2020, 2021). The relation between salinity and DO in this study was not found significant ($P > 0.3$) in the profiles. Some salinity profiles showed inverse relation with DO profiles while others showed opposite or no relation.

pH determines the acidity or alkalinity of a water system. It regulates the chemical and biological states of nature water. The changes in pH bring the dissociation of weak acids and bases that affects the toxicity of most compounds in water. Hence, the ability of water to support life is a function of pH (Simon & Beevers 1952). Water pH was found between 7.5 and 8.7 in the profiles during the study period, in three stations. During the study period, this stability of values at the mouth of the estuary can be explained by the alkalizing effect of marine waters, and upstream by the marly and calcareous nature of the geological formations of the Bouregreg catchment area, thus promoting the release of carbonates and bicarbonates, which increases the pH (Benmessaoud 2007). The pH profiles rarely showed any major stratification in the stations. The pH is defined as negative log to H+ ion concentration. As temperature increases, H+ concentration increases due to increased activity and there is a drop in pH. For example, pH of water at 100 °C is 7.47 and that at 1000 °C is 6.14. Also, the variation of pH with temperature is just one scale for a temperature difference of 1,000 °C. Thus, the relationship between pH and temperature and hence DO in the estuary was found not significant ($P > 0.05$) in the profiles. DO and pH would increase when photosynthesis by aquatic plants removes carbon dioxide (CO_2) from the medium and decline during respiration by aquatic organisms and decomposition by decomposers release CO_2 into the medium (Mistry *et al.* 2019). The observed pH range (7.5–8.7) in the surface layer of the stations suggests a reasonable extent of photosynthesis by aquatic plants in the surface of the estuary. While a nearly similar pH range (7.0–8.0) in the bottom layer suggests insufficient respiration and decomposition at the bottom of the estuary. In addition, water mixing is also responsible for similar pH in the profiles (Muduli & Pattnaik 2020; Rouf *et al.* 2022).

Transparency of the Bouregreg estuary was also observed during the study period and the records are shown in Table 2. The values ranged from 16 to 21 cm. The range of transparency observed in the estuary was noticeably low and represents (in general) extensive turbid water.

Table 2 | Transparency of water in the head of the Bouregreg estuary

Station	Tide	Transparency (cm) 10/11/2021	20/03/2022	02/07/2022
Station 1	HW	20	18	21
	LW	18	17	19
Station 2	HW	19	18	–
	LW	17	17	18
Station 3	HW	16	16	17
	LW	17	18	17

HW = high water; LW = low water.

CONCLUSIONS

The Bouregreg estuary has significant ecological importance in Morocco. Despite its ecological importance, the estuary is seldom studied, and consequently, the ecosystem's structure and function are seldom known. Following a comprehensive field investigation with vertical profiles of the selected water quality parameters (10/11/2021, 20/03/2022, and 02/07/2022), the purpose of this study is to explore the vertical stratification of DO and its association with salinity, temperature, pH, and transparency. DO concentration ranged from 5.5 to 11.8 mg/L with maximum three units (mg/L) of variation in the depth profiles and demonstrated an inconsistent stratification pattern. Relatively low DO concentration near the surface layers and high near the bottom layers were remarkably noticed in most of the sampling periods and is associated with cooler bottom waters complimented by gravitational circulation and mixing. Strong freshwater flow in the surface layer, existence of estuarine gravitational circulation, and lack of oxygen consumption in the bottom layer due to high sediment particles ameliorated the pattern of higher DO concentration in bottom and lower in the surface layer of the estuary. The DO variations are significant over the tidal cycle with higher DO values during low tides than high tides that are attributed to the higher saline water during high tides. Variations of DO are more influenced by the temperature and salinity than pH. By analyzing the DO profile in the Bouregreg estuary of Morocco, this study will provide considerable insights into ecosystem dynamics relating to DO profile. In perspective of this research, actual work of the authors focuses on 1-D/2-D modeling of DO along an estuary axis, which may give novelty in results and information for scientific community (Preliminary results: see Appendix, Supplementary material).

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

APHA, AWWA & WEF 1995 *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, American Water Works Association & Water Environment Federation, Washington, DC, USA. p. 1000.

Averill, B. A. & Eldredge, P. 2012 Effects of temperature and pressure on solubility. *Principles of General Chemistry*. Libre Texts, 1577–1589. Available at: https://2012books.lardbucket.org/books/principles-of-general-chemistry-v1.0/index.html.

Behar, S., Byrne, J. & Dickason, C. N. 1996 *Testing the Waters: Chemical and Physical Vital Signs of A River*, 1st edn. Kendall Hunt Publishing Company, River Watch Network Montpelier, Vermont.

Benmessaoud, F. 2007 *Physico-Chemical, Metallic and Bacteriological Quality of the Waters of the Bou Regreg Estuary and Impact on the Biology and Demography of Venerupis Decussate (LINNE, 1758) and Cardium Edule (LINNE, 1767)*. *PhD Thesis*, Faculty of Sciences of Rabat. University Mohamed V.

Brahimi, A. & Chafi, A. 2014 Etude écotoxicologique de l'oued Za et de son affluent Oued Tizeghrane (Basse Moulouya, Maroc Oriental) [Ecotoxicological study of Oued Za and its tributary Oued Tizeghrane (Lower Moulouya, Eastern Morocco)]. *Journal of Materials and Environmental Science* **5**(5), 1671–1682.

Bu, X., Dai, H., Yuan, S., Zhu, Q., Li, X. & Zhu, Y. 2021 Model-based analysis of dissolved oxygen supply to aquifers within riparian zones during river level fluctuations: dynamics and influencing factors. *Journal of Hydrology* **598**, 126460. doi:10.1016/j.jhydrol.2021.126460.

Cheggour, M., Chafik, A., Fisher, N. S. & Benbrahim, S. 2005 Metal concentrations in sediments and clams in four Moroccan estuaries. *Marine Environmental Research* **59**(2), 119–137.

Cherkaoui, E. 2006 *Structure and Organization of the Macrozoobenthic Stands of the Estuary of the Bouregreg After the Construction of the dam*. *PhD Thesis*, Faculty of Sciences of Rabat, University Mohamed V.

Cherkaoui, E., Hily, C. & Bayed, A. 2005 Structure and distribution of intertidal benthic stands in an estuary of North Africa: the estuary of Bou Regreg. *Marine Life* **15**(1–2), 29–41.

Davidson, N. & Council, N. C. 1991 Nature conservation and estuaries in great Britain. In *Nature Conservancy Council Peterborough*.

El Amraoui, M., Salama, Y., El Amraoui, B., Lazrak, N. & Mounkad, M. 2015 Evaluation of the physicochemical and some trace elements of the surface waters of the Moroccan atlantic estuary: case of the estuary of the river Bouregreg. *Carpathian Journal of Earth and Environmental Sciences* **10**(2), 189–198.

El Harim, A., Cherkaoui, E., Khamar, M. & Nounah, A. 2019 The impact of the depollution project on the quality of the estuarine ecosystem of bouregreg (Morocco atlantic coast). *International Journal of Conservation Science* **10**(4), 763–772.

El Harim, A., Cherkaoui, E., Khamar, M. & Nounah, A. 2021 Assessment of the water quality of the bouregreg estuary after the depollution project. *International Journal of Conservation Science* **12**(1), 267–280.

Haddout, S., Priya, K. L. & Adarsh, S. 2020 A predictive model for salt intrusion in estuaries applied to the Muthupet estuary (India) and Bouregreg estuary (Morocco). *ISH Journal of Hydraulic Engineering* **26**(4), 430–447.

Haddout, S., Priya, K. L. & Samad, B. 2021 Testing thermodynamics method for salt intrusion during infrequent astronomical event. *Marine Georesources & Geotechnology* **39**(10), 1139–1146.

Hauer, F. R. & Hill, W. R. 2007 Temperature, light, and oxygen. In: Hauer, F. R. & Lamberti, G. A. (eds). *Methods in Stream Ecology*. Academic Press, London, pp. 103–117.

Hume, T. M. & Herdendorf, C. E. 1988 A geomorphic classification of estuaries and its application to coastal resource management–a New Zealand example. *Ocean and Shoreline Management* **11**(3), 249–274.

Ji, X., Shang, X., Dahlgren, R. A. & Zhang, M. 2017 Prediction of dissolved oxygen concentration in hypoxic river systems using support vector machine: a case study of Wen-Rui Tang River, china. *Environmental Science and Pollution Research* **24**, 16062–16076. doi:10.1007/s11356-017-9243-7.

Liblik, T., Wu, Y., Fan, D. & Shang, D. 2020 Wind-driven stratification patterns and dissolved oxygen depletion off the Changjiang (Yangtze) Estuary. *Biogeosciences* **17**(10), 2875–2895.

Lin, J., Xie, L., Pietrafesa, L. J., Shen, J., Mallin, M. A. & Durako, M. J. 2006 Dissolved oxygen stratification in two micro-tidal partially-mixed estuaries. *Estuarine, Coastal and Shelf Science* **70**(3), 423–437.

Mistry, A. N., Ganta, U., Chakrabarty, J. & Dutta, S. 2019 A review on biological systems for CO 2 sequestration: organisms and their pathways. *Environmental Progress & Sustainable Energy* **38**(1), 127–136.

Muduli, P. R. & Pattnaik, A. K. 2020 Spatio-temporal variation in physicochemical parameters of water in the Chilika Lagoon. In: Finlayson, C. M., Rastogi, G., Mishra, D. R. & Pattnaik, A. K. (eds). *Ecology, Conservation, and Restoration of Chilika Lagoon, India*. Springer, Cham, pp. 203–229.

Pereira, L. C. C., de Oliveira, S. M. O., da Costa, R. M., da Costa, K. G. & Vila-Concejo, A. 2013 What happens on an equatorial beach on the Amazon coast when La Niña occurs during the rainy season? *Estuarine, Coastal and Shelf Science* **135**, 116–127.

Pritchard, D. W., 1967 What is an estuary: physical view point. In: Lauff, G. H. (ed.). *Estuaries. No. 83.* American Association for the Advancement of Science, Washington, DC., USA, pp. 3–5.

Priya, K. L., Haddout, S. & Adarsh, S. 2018 Settling velocity of fine suspended sediments in Muthupet estuary, India and Bouregreg estuary, Morocco. In *Abstract of International Conference on Sustainable Technologies on Intelligent Water*. pp. 16–19.

Priya, K. L., Haddout, S. & Adarsh, S. 2021 Settling Velocity of Suspended Sediments in Muthupet Estuary, India and Bouregreg Estuary, Morocco. In: Pandey, A., Mishra, S. K., Kansal, M. L., Singh, R. D. & Singh, V. P. (eds). *Climate Impacts on Water Resources in India*. Springer, Cham, pp. 125–146.

Priya, K. L. A., Haddout, S. & Casila, J. C. C. 2022 Implications of turbulent shear on clay floc break-up along the Atlantic estuary (Bouregreg), Morocco. *International Journal of Sediment Research* **37**(2), 248–257.

Rouf, M. A., Islam, M. J., Roknuzzaman, M. R., Siddique, M. N. & Golder, M. R. 2022 Vertical profile of dissolved oxygen and associated water variables in the Pasur-Rupsha estuary of Bangladesh. *Heliyon* e10935 (in press).

Sarker, M. J., Tanmoy, M. H., Islam, M. S., Nazrul, K. M. S., Hossen, S. & Ali, M. M. 2021 Seasonal variation in the coastal water phytoplankton communities and their environmental responses at upstream and downstream of the steep Naf River in the south-western Bay of Bengal. *International Journal of Aquatic Biology* **9**(5), 309–325.

Savenije, H. H. G. 2005 *Salinity and Tides in Alluvial Estuaries*. Elsevier, Amsterdam.
Savenije, H. H. G. 2006 Comment on 'A note on salt intrusion in funnelshaped estuaries: application to the Incomati estuary, Mozambique' by Brockway *et al.* (2006). *Estuarine, Coastal and Shelf Science* **68**, 703–706.
Savenije, H. H. G. 2015 Prediction in ungauged estuaries: an integrated theory. *Water Resources Research* **51**(4), 2464–2476.
Simon, E. W. & Beevers, H. 1952 The effect of pH on the biological activities of weak acids and bases I. The most usual relationship between pH and activity. *The New Phytologist* **51**(2), 163–190.
Wei, X., Kumar, M. & Schuttelaars, H. M. 2017 Three-dimensional salt dynamics in well-mixed estuaries: influence of estuarine convergence, Coriolis and bathymetry. *Journal of Physical Oceanography*. **47**(7), 1843–1871.
Zellou, B. & Rahali, H. 2017 Assessment of reduced-complexity landscape evolution model suitability to adequately simulate flood events in complex flow conditions. *Natural Hazards* **86**(1), 1–29.

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