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Optical characterization of coastal lagoons in Tunisia: Ecological assessment to underpin conservation

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A B S T R A C T

Ghar El Melh is a shallow lagoon (average depth of 0.8 m) that has undergone a eutrophication process due to growing human pressures. To obtain a global frame of the ecosystem functioning, an optical and an ecological classification were used in parallel. Downwelling and upwelling spectral irradiances were measured in situ in 22 sampling stations across the water body; then Apparent Optical Properties (AOPs), namely reflectance $R(\lambda)$ and vertical attenuation coefficient $K_d(\lambda)$ were calculated for each wavelength of visible spectrum, furnishing typical spectra from turbid waters, rich in dissolved and suspended matter. From water samples of the same stations the concentrations of OASs (Optically Active Substances), i.e. Chromophoric Dissolved Organic Matter (CDOM), Non-Algal Particulate (NAP) and Phytoplankton, were assessed. The use of an optical classification for water bodies rich in TSM and CDOM, integrating AOPs and OASs, highlighted a great spatial heterogeneity, well overlapping with hydrology and human impacts patterns. A modified version of the Ecological Evaluation Index (EEI), considering the macrophyte distribution (based on a visual assessment of macrophyte coverage, without quantitative sampling) was then used, highlighting an intermediate ecological condition, despite high water turbidities. The integrated use of both systems thus furnished a complete characterization, rapidly detecting the most impacted sectors and the possible primary causes. The method might be applied as a monitoring procedure in other Mediterranean coastal lagoons, with the aim to adopt a common conservation strategy for these important transitional water bodies.

1. Introduction

Coastal lagoons have been exploited by humans because of their high productivity and biodiversity. In these areas, many ecotones occur (water/sediments, fresh/brackish/sea waters, atmospheric/water circulation, pelagic/benthonic communities), which, together with supplies from the catchment area and the sea, may cause the establishment of strong gradients. This results in a higher capacity for producing energy in comparison to marine environments (Gönenç and Wolfin, 2005). Coastal lagoons have been used by humans for settlements, fishing, aquaculture and agriculture, putting pressures on these ephemeral and dynamic systems. This is especially true for Mediterranean coastal lagoons because of their shallow waters and low volumes, which make them vulnerable to global climate changes more than inland lagoons. In the Mediterranean sea, temperatures are expected to rise from 0.2 to 0.6 °C each decade (IPCC, 2007), engendering a rise of the sea level that seriously threatens the integrity of such transitional ecosystems (Eisenreich, 2005). In Tunisia, lagoon environments are important both from an ecological and economic points of view, covering an area of about 1100 km^2 from the northern to the southern coasts of the country. Currently, almost all these transitional water bodies undergo environmental degradation, due to pollution (domestic and industrial waste waters, organic and mineral nutrients rich waters from catchments exploited for farming, industries, etc.) and recent increases of sea-tourism activities. The latter results in the building of hotels, roads, ports, marinas, etc., almost never planning for the possible impacts on ecosystems. One of the main risks from these human stressors is the eutrophication of the Tunisian coastal lagoons, which is also the case for the Ghar El Melh lagoon, situated in Tunisia N-W. In 2008 an optical and ecological classification was carried out, to evaluate whether the existing methodologies for coastal water investigation were suitable for transitional water bodies, and how these methodologies should be improved, with the main goal to provide a practical, repeatable monitoring procedure, useful for the management and conservation of Mediterranean coastal lagoons.

2. Materials and methods

2.1. The study area

The Ghar El Melh lagoon complex is located on the north-western side of the Gulf of Tunis (10°08′–10°15′ E; 37°06′–37°10′ N) between Tunis and Bizerte. Currently the lagoon complex has an about elliptical form, 7 km long and 4.5 km wide, with an average depth of 0.8 m

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(0.2 m and 3.8 m minimum and maximum, respectively) (SCET_ERI, 2000). In the past, Ghar El Melh lagoon was fed by *Oued* Majerda, a river that currently has its mouth displaced southward. Now the main water supplies come from streams drained by the catchment area, together with atmospheric precipitations falling down directly on the surface.

The main threat to the stability of the ecosystems here is the sediment drift modification due to the construction of a harbor close to the opening channel, together with issues linked to water quality, caused by poor regulation and management of recent touristic and agricultural developments. In this part of Tunisia a consistent rise of tourism is responsible for an augmented fresh water demand, mainly during the summer season, associated with increased sewage water production, not subject to any kind of sanitization treatment before returning to the catchment area. Also, agricultural methods are being altered, and there is no regulation of the types and amount of pesticides, fertilizers and other organic and mineral substances used by local farmers to increase their crops.

2.2. Optical properties and classifications

In the paper we define irradiance (E) as the luminous radiant flux per surface unit (in W/m^2); $E = d\Phi/dS$. To calculate water optical properties, the main physical quantities to be measured are downwelling irradiance (E_d) on a plane horizontal surface, due to the radiation coming from the superior semi space, and upwelling irradiance (E_u), the same measure due to the radiant flux rising from the inferior semi space (Kirk, 1994). By taking measurements of upwelling and downwelling irradiance, in the entire spectrum of visible light at different depths, it is possible to calculate two important optical properties of waters:

Reflectance (R): the upwelling on downwelling irradiance ratio, for any specific wavelength, roughly indicating the backscattering/absorption ratio, calculated as follows:

$$R(\lambda) = E_u(\lambda)/E_d(\lambda). \tag{1}$$

Vertical attenuation coefficient for downwelling irradiance (K_d), which expresses the E_d variation with depth z; that for each considered wavelength can be calculated as:

$$K_d(\lambda) = -[lnE_{d1}(\lambda) – lnE_{d2}(\lambda)]/(z_2 – z_1). \tag{2}$$

Such characteristics are called the Apparent Optical Properties (AOPs) because they are not only properties of the radiant field, but also of the water body. They are closely associated with the so-called Inherent Optical Properties (IOPs) of water, allowing to use AOPs instead of IOPs, which are more difficult to estimate (Gordon and Morel, 1983; Gordon et al., 1975; Kirk, 1984). Therefore, if measured at high solar elevation, the spectral variations of R and K_d can be used to classify natural waters based on the different Optically Active Substances (OASs) that contribute to light attenuation. These include Chromophoric Dissolved Organic Matter (CDOM, also called “yellow substance”), Non-Algal Particulate (NAP, or non-phytoplanktonic fraction of TSM, or tripton) and phytoplankton. Previous studies have investigated methods to measure the optical properties of natural waters and create optical classifications. One of the first methods, based on K_d, was created by Jerlov (1976), which proposed a scale from 1 to 9 types for coastal waters. As this method was created mainly to analyze oceanic waters, normally poor in organic matter; it is not uncommon that coastal basins display attenuation values exceeding up to eight times those of the most turbid Jerlov's class, type 9 (Reinart et al., 2003). Morel and Prieur (1977) elaborated an optical classification based on the reflectance spectra $R(\lambda)$, separating the so-called case 1 and case 2 waters. In the former case, phytoplankton is optically dominant (pelagic waters), whereas in the latter one the main role is played by NAP or CDOM (inland and coastal waters). This classification was re-examined by Prieur and Sathyendranath (1981), who considered absorption spectra. Another optical classification applicable mainly to inland waters was proposed by Kirk (1980), distinguishing waters on their prevalent absorption components. With the aim to focus on case 2 waters and to consider the high diversity existing among them, an alternative classification was proposed by Reinart et al. (2003), planned for lakes, but suitable for all coastal waters in small and shallow bays, influenced by river contributions and affected by sediments suspension, i.e. all kind of basins comparable to lakes. The method is based on K_d, R and Secchi depth, but also employs OASs concentrations; the criterion for including a particular type of water in a particular optical class is found by the K-means clustering technique. Waters belonging to class C (Clear) show a relatively small amount of OASs, are transparent, have the smallest K_d and their R is about 2%, with the optical properties determined mainly by phytoplankton pigments. In M (Moderate) waters the color is modified mainly by CDOM. Class T waters are turbid but not highly eutrophic and have suspended particles (both organic and mineral) causing high scattering and high R values. Such water bodies are shallow and their suspended matter may contain a rather large amount of mineral particles from the bottom. The V (Very turbid) waters present a large amount of Chl_a (>60 mg m^{-3}), generally during phytoplankton blooms. Type V is typical of shallow eutrophic water bodies, as already described by Kirk (1981). Class B (Brown) are brownish-water humic basins, having high levels of CDOM, in particular of humic acids; K_d, is also very high, while R is extremely low (less than 0.2%). We chose to use this method to obtain a fine spatial classification of the Ghar El Melh waters, dominated by dissolved and suspended matter.

2.3. Sampling protocol

In April 2008, we sampled a set of 22 stations in the lagoon, chosen to cover a range of environmental conditions, in which measures of spectral E_d and E_u (between 400 and 730 nm) were taken just above the water surface, at 10 cm and 50 cm of depth (when this was allowed by the depth of the basin) or otherwise at the maximum possible depth. Irradiances were measured by means of a portable diode-array spectroradiometer (AvaSpec-2048, Avantes), to which a 50 µm fiber optic was connected, with a cosine collector (CC3-UV); the measured spectra were acquired and visualized through a laptop. Irradiance measures were taken near noon with calm waters and reduced cloudiness conditions to avoid strong fluctuations of the underwater radiant flux (Kirk, 1994). Secchi disk measures were not taken because of the limited basin depth and an indirect estimate was calculated from the measured K_d values: $Z_{Secchi} = 2/K_d$ (Shifrin, 1988). At the same time, for each station superficial water samples were collected to measure their main components in the laboratory. TSM (Total Suspended Matter, as a proxy of NAP) was determined according to Strickland and Parsons (1972) modified by Van der Linde (1998) for the salt wash procedure. To determine CDOM absorption the protocol of Bricaud et al. (1981) was applied, using the interpolation method of Stedmon et al. (2000) and Twardowski et al. (2004); the concentration was finally obtained by the approximation of Nyquist (1979). Chl_a (chlorophyll a) was extracted and analyzed following the procedure of Lazzara et al. (2010). A visual survey was also carried out in the whole basin, by defining ecologically uniform, non-overlapping permanent-polygons (PPs), in which the percentage cover of benthic macrophytes (angiosperms, epiphytic algae and macroalgae) was assessed. A modified version of the Ecological Evaluation Index (EEI) by Orfanidis et al. (2001) was then applied, integrating these snapshot data collected during spring with those described by Rasmussen et al. (2009), referring to February 2003 and September 2004, with the aim to have a more complete characterization of the ecosystem features. The index assumes that shifts in the quality of structure and functioning of transitional water bodies can be detected by separating benthic macrophytes into two Ecological State Groups (ESGs I, II) typical of a pristine or degraded ecological state, respectively (see Viaroli et al., 2008). In all the Permanent-Polygons, the percentage cover was visually evaluated to establish abundance (%) of each ESG, and the EEI of each PP was determined. Scores were then multiplied by the relative surface area of each PP and then summed, giving the final weighted EEI.

3. Results

3.1. Optical properties

The main results on OASs concentrations are summarized in Table 1. TSM (proportional to NAP contents) was high and its organic fraction was around 20%, making NAP more likely to produce scattering than absorption during the light attenuation process. Chl_a concentrations were low in the whole basin, indicating a reduced phytoplankton presence, whereas CDOM contents resulted relatively high, in the range of coastal and estuarine waters (Kirk, 1994) and of inland waters (Binding et al., 2008).

In Table 1 are also shown some important summaries relative to the lagoon optical properties. The values of reflectance at 10 cm from the surface (R_{10}) represent each station, due to the smaller bottom influence at this depth. The values in the green band (R_{555}) were quite high (1%–19%), and the blue/green reflectance ratio (443/555) was smaller than 1, indicating a strong absorption of the blue light (Ouillon and Petrenko, 2005). The analysis of reflectance spectra confirmed that the whole basin was constituted of case 2 waters, with a typical peak at about 570 nm (where absorption of CDOM, water and pigments is smaller) and a minimum at 670 nm, due to the chlorophyll *a* absorption peak. Analyzing the K_d spectra, calculated between 10 and 50 cm of depth, a great variability of the light attenuation was observed (Table 1). Based on the features described by Prieur and Sathyendranath (1981), two patterns were recognized: 1) in almost all stations CDOM strongly absorbed light, with reduced contribution of phytoplankton, but 2) in few cases the scattering, ascribable mainly to particulate matter (Gordon and Morel, 1983; Morel and Prieur, 1977), prevailed on the absorption of photons. To apply the optical classification of Reinart et al. (2003), based both on AOPs and on OASs contents, once calculated the average R and K_d in the visible spectrum, we obtained Secchi depth for each sampling station, by the approximation of Shifrin (1988). It was surprising to discover that all the five optical classes were present in the lagoon, giving rise to a consistent spatial heterogeneity, not detected by classical optical methods. The spatial distribution of classes was consistent with the results from OASs analysis and with previous data on lagoon hydrodynamics (Moussa et al., 2005; Thompson et al., 2009). As shown in Fig. 1, waters were clear close to the channel of communication with the sea and moderate in the northern sector, becoming very turbid in the central and southern

Table 1
Main summaries for Ghar El Melh waters in April 2008. For Optical Active Substances (OASs): Total Suspended Matter (TSM), Chlorophyll$_a$ (Chl_a) and Chromophoric Dissolved Organic Matter (CDOM). For Apparent Optical Properties (AOPs): mean vertical attenuation coefficient in the visible domain (K_d), reflectance (R_{10}) at 555 nm and blue/green reflectance ratio.

	Mean	Min.	Max.	St. Dev.	N
TSM (mg/l)	30.25	13.19	46.84	12.73	11
Chl_a (mg/m^3)	1.69	0.41	6.43	1.50	17
CDOM (mg/l)	1.50	0.67	2.21	0.43	13
K_d *vis* (m^{-1})	2.81	1.23	5.29	1.30	13
R_{10} 555	8.8%	0.9%	19.1%	0.05	13
R_{10} ratio (443/555)	0.32	0.19	0.52	0.09	13

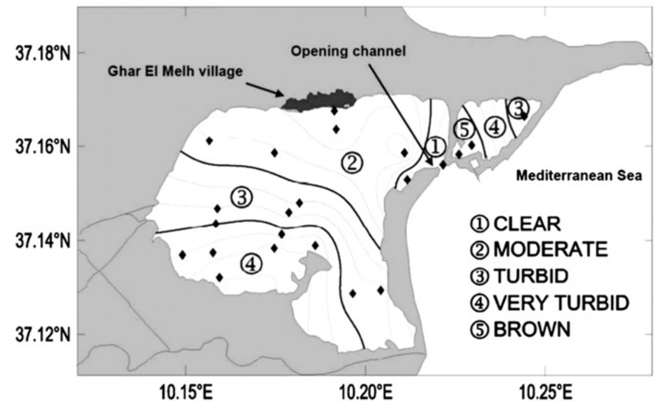

Fig. 1. Reinart's optical classification applied to the waters of Ghar El Melh and Sidi Ali El Mekki lagoon system (north-west Tunisia) in April 2008.

areas. Also the Sidi Ali El Mekki waters were very turbid, even brown, due to the minimal depths and sediments suspension by wind.

3.2. Ecological assessment

For the Ghar El Melh lagoon we also used data from Rasmussen et al. (2009), not considering the small Sidi Ali El Mekki lagoon, so the modified version of EEI was not applied to this part of the system. Based on the results from spatial analysis of OASs and AOPs, we divided the main basin into three PPs:

1. The part near the opening in the sandbar and at N-E of it, with moderate turbidity and smaller contents of substances, which represents about 10% of the total surface;
2. The central and N-W sectors, more turbid, with higher contents of OASs and slower rates of exchange with the sea, covering approximately 60% of the basin;
3. The S-W area, which showed higher turbidity and higher contents of OASs, due to the slow water turnover, including about 30% of the lagoon.

In the first sector we could observe, in agreement with the literature (Shili et al., 2002), a considerable cover of *Ruppia cirrhosa*, a perennial seagrass classed in ESG I; this species decreased toward the central part of the lagoon, where it was about equivalent to the covering of *Cladophora* algae, filamentous opportunistic species classed in ESG II. These latter species became highly dominant in the S-W zone, where *R. cirrhosa* almost disappeared. Therefore, in the first PP the EEI was 8 (good ecological status), in the second one it was 6 (moderate) ecological class, while in the third one we obtained a value of 2 (bad status). Hence the weighted EEI for the entire lagoon was 6.8, i.e. a good, almost moderate ecological condition.

4. Discussion and conclusions

Although a single spring survey cannot offer an exhaustive frame of such a complex ecosystem as a coastal lagoon, the results indicated some interesting possibilities for future monitoring strategies.

First of all, it was stressed the utility of taking in situ light measures, easily performed by means of a portable diode-array spectrometer. AOPs analysis proved to be a valid tool for the rapid assessment of water contents of phytoplankton, CDOM and NAP, as the laboratory analyses of water samples confirmed.

Moreover, the use of the optical classification by Reinart et al. (2003) offered, in a rapid and repeatable way, a detailed picture of the actual conditions of the Ghar El Melh lagoon and the connected Sidi Ali El Mekki lagoon, revealing a considerable spatial heterogeneity, which resulted to be consistent with the human impacts acting on these ecosystems. Waters were classified as M in the North of the basin, where marine influence was still acting and the small fishermen's village produced reduced impacts, quickly turning to V where the depths decreased, permitting to wind to raise sediments from the bottom (Moussa et al., 2005; Thompson et al., 2009), and where inputs from cultivated lands were stronger. Briefly, a relation was observed between the types of human activities and the achieved optical classification. Therefore water optical classification may represent a valid tool for conservation purposes, permitting a rapid identification of the sectors more affected by human impacts. Moreover, the graphical representation of the optical results over time, with special reference to seasonal trends, may permit to managers and other stakeholders to follow the basin evolution and to understand the effect of meteorological variables on its waters chemistry, furnishing useful indications for planning the best conservation strategy.

However, to assess the global ecological status of the lagoon, the need rose for a tool based on ecosystem biotic components, not considering OASs contents, thus permitting to integrate the optical characterization. A modified version of the EEI by Orfanidis et al. (2001) was applied, using just a visual survey of the macrophytes cover, which may be proposed for other ecosystems too, where the sampling of vegetation or fauna may be restricted. Being specific for shallow coastal lagoons, EEI avoids some common errors of classic limnological techniques, based on water chemical composition; here we found that, despite high contents of solved and suspended matter, the lagoon actually had a quite good ecological status, closer to mesotrophy than to the eutrophication that was supposed in the Introduction of this paper. The lack of any linear relations between optical and trophic classifications of coastal water bodies was highlighted: as already stressed by Arst and Reinart (2009), oligotrophic waters are usually clear, while eutrophic or dyseutrophic ones tend to be very turbid or brown, but turbidity is not necessarily an index of bad ecological quality, so it would be incorrect to infer one feature from the other one. The best practice should be, as we did, the parallel assessment of both aspects. To conclude, we know that the main threats to the Ghar El Melh system equilibrium are two. First of all, a reduced contribution of marine water in most of the basin, which favors the accumulation of suspended and dissolved matter far from the channel; and secondly, uncontrolled inputs of fertilizer compounds from agricultural lands at S-W, which could rapidly produce a worsening of the lagoon water quality, leading to the clearing of a threshold-value, after which a return could be impossible (de Wit et al., 2001; Muradian, 2001). Both phenomena were clearly detected by the described optical classification, while their effects on the biotic component were highlighted using the ecological index. Thus, in this study a monitoring procedure is suggested, based on in situ light penetration and benthic macrophytes cover measures, which is highly informative, not invasive or destructive, easy and cost-effective to perform. Moreover, the proposed method can be easily understood by stakeholders, a necessary requirement for its correct and continuous application. We hope that this work will be of some utility not just for this specific case-study, but also for other transitional water bodies endangered by human pressures along Mediterranean coasts, having a great value, both economic and touristic, but first of all for environmental conservation.

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