Ecological Informatics 14 (2013) 79–83

Contents lists available at SciVerse ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf

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

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ARTICLE INFO

Article history:
Received 24 January 2012
Accepted 30 November 2012
Available online 8 December 2012

Keywords:
Coastal lagoon
Optical properties
Macrophytes
Ecological assessment
Monitoring procedure

ABSTRACT

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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http://dx.doi.org/10.1016/j.ecoinf.2012.11.011

(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