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# The present environmental scenario of the Nador Lagoon (Morocco)

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## Abstract

In this paper, we present a multivariate approach (waters, sediments, microfauna) concerning the environmental state of the Nador Lagoon (NE Morocco). The normal water quality parameters (salinity, pH, nutrients) of the dominant marine flows are altered by local fecal water effluents, urban discharges, sewages derived from a water treatment station, and residues originated in a slaughterhouse. The geochemical analyses carried out in surficial sediment samples show very high concentrations of all metals studied near an old iron mine and moderate contents between Nador and its treatment station. Ostracods are good bioindicators of these environmental impacts, with the presence of a highly brackish assemblage in the quieter, more confined areas or the appearance of opportunistic species under hypoxic conditions. In addition, these microcrustaceans are absent in polluted bottom sediments or areas with high hydrodynamic gradients, whereas they decrease in both density and diversity if the subaerial exposure increases.


*Keywords:* Environmental diagnostic; Waters; Sediments; Ostracods; Lagoon; Morocco

## 1. Introduction

In the past three decades, numerous investigations have been focused on the environmental analysis of coastal lagoons. Some of them have analyzed the physicochemical quality of waters (Cotner et al., 2000; Kaimoussi et al., 2002; Medina-Gómez and Herrera-Silveira, 2003), the heavy metal contents of the bottom sediments (Bellucci et al., 2002; Maanan et al., 2004; Shumilin et al., 2001), the impact of different anthopogenic activities on the aquatic primary production (Knoppers, 1994), or the metal concentrations in soft tissues of different macrofaunal groups (Cossa, 1989; Cheggour et al., 2001; Labonne et al., 1998).

Different microfaunal groups have been proposed as bioindicators in these coastal areas. According to Rinderhagen et al. (2000), a bioindicator is a collective of organisms that give information about the environmental state, with effect variables being their mere presence or absence, abundance, age structure, or a statistical index applied to their populations. They make it possible to assess the effects of natural changes and/or several anthropogenic impacts, with the presence of sensitive species within very different groups such as harpacticoid copepods, turbellarians, foraminifers, diatoms, or dinoflagellate cyst (Alve, 1995; Cooper and Brush, 1991; Lampadariou et al., 1997; Lee et al., 2001; Willard et al., 2003; Yanko et al., 1999).

Ostracods are usually included among this low-size group and present hopeful perspectives as bioindicators of changing environmental conditions in recent and Quaternary environments (Anadon et al., 2002; Boomer and Eisenhauer, 2002; Malard et al., 1996; Mosslacher,

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2000). Their faunal composition, population density, and diversity are variable, depending on various environmental factors such as water temperature, salinity, water depth, grain size, dissolved oxygen, nutrient concentration, or heavy metal content (i.e., Álvarez Zarikian et al., 2000; Bodergat et al., 1998; Carbonel, 1980; Cronin and Vann, 2003; Ruiz et al., 2004a). In addition, several investigations pointed out the almost instantaneous population response to anthropogenic impacts, such as oil spills or industrial sewages (Bodergat et al., 1991; Kaesler et al., 1979; Mostafawi, 2001).

In this paper, we analyze the potential of this group as possible bioindicator of environmental changes induced by the natural evolution and/or anthropogenic activities in the Nador lagoon (NE Morocco). For this purpose, its population distribution was compared with the bottom grain size and vegetation, water nutrient contents, heavy metal levels in sediments, hydrodynamics, and the main human-induced inputs in the lagoon margins.

## 2. Study area

### 2.1. Geographical features and hydrodynamics

The Nador lagoon is the second lagoon complex of northern Africa (115 km$^2$), the broadest paralic environment of Morocco and the only one located along the Mediterranean coast of this country. It comprises a broad area bounded to the northwest by the Beni Ensar city, to the southeast by the village of Kariat Arekmane, and to the southwest by the northern extremity of the Bou Areg plain (Fig. 1). This lagoon is protected by a NW–SE elongated sandy spit (25-km length), with an average width between 300 and 400 m (2 km near the southeastern corner) and a small height (<20 m), only interrupted by an artificial inlet limited by two jetties that communicates it with the Mediterranean Sea. The remaining adjacent areas are basically plain, except in the northwestern corner because of the presence of the Gourougou stratovolcano (887-m height), and the southwestern border, occupied by some elevations belonging to the Kebdana Mountains (932-m height).

The external hydrodynamics of this coastal area depends on the tidal regime, the littoral drift currents, and the prevailing waves. The tidal regime of this Mediterranean region is microtidal and semidiurnal, increasing toward the eastern and reaching 0.35 m near the lagoon inlet (Brethes and Tesson, 1978). The coastal drift currents are derived from the West Alboran Gyre and have the greatest effects on the sediment redistribution of this littoral. The net sediment flow is oriented toward the east, with a low annual transport rate of sediment in this direction (168 m$^3$/yr; Inani, 1995). The more frequent waves proceed from the E (21.3%), ENE (15.2%), and W (17.4%). The mean wave height is 1 m, with a mean period of 5 s for these directions.

The internal hydrodynamics of the Nador lagoon is joined to three types of hydrological resources: (a) the marine waters passing through the artificial inlet, which are always dominant; (b) the hydrogeological contributions from two aquifers: Gareb, located southern Selouane, and Bou Areg, situated near the southern margin of the lagoon; and (c) the surface water inputs, with the periodic flows of 10 small streams ("oueds"). Among them, the Selouane stream is the most important, bringing the urban/industrial

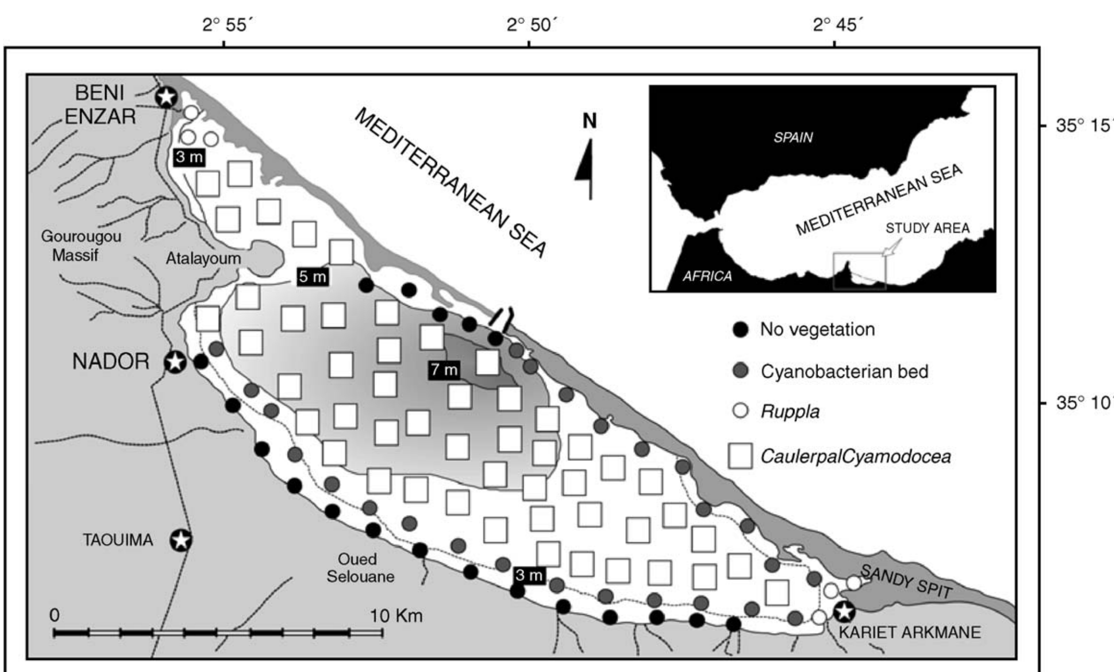



Fig. 1. Location of the Nador Lagoon, with inclusion of the main towns (stars), some geographical features cited in the text, bathymetry, and bottom cover.

wastes of the Selouane village into the lagoon during the wet season.

In the lagoon, these different flows are oriented by the internal currents, which have an hourly sense from the artificial inlet toward the NW coast, moving about the internal face of the sandy spit and the internal lagoon margin (Erimesco, 1961; Guelorget and Perthuisot, 1983).

### 2.2. Anthropogenic actions

The Nador lagoon is subjected to an increasing anthropogenic pressure owing to the economic activities in the adjacent zones. The public treatment station of Nador (TSN), constructed in 1980 and amplified for a population of 100,000 in 1990 become insufficient due to the expansion of this region and presents frequent errors in both the electric circuits and the electromechanical systems. This station only provides partial biological treatment, without any additional physicochemical purification, microbiological control, or disinfection. Other towns and villages (Beni Enzar, Kariet Arkmane) also drain their fecal waters directly in to the lagoon without any previous treatment.

Some industrial sewages coming from the Selouane industrial area are poured out to the lagoon during the wet station. This area has a waste station, without later disinfection of the treated waters, which are emptied into the Selouane Oued and flow directly into the lagoon. Other water pollution sources are the numerous irrigation channels and oueds that drain the southern border of the lagoon, carrying the liquid/solid residues of a broad area occupied by small farming exploitations.

A tailing pond system is utilized in the TSN and may cause an additional source of pollution to the lagoon, due to the infiltration of heavy metals and the utilization of the solid residues as vouchers by farmers. The same process was used for extraction of iron minerals near an old iron mine located in the Atalayoum promontory.

Moreover, remains of bricks, glazed tiles, concrete, cement, or scrap iron are dumped and stockpiled in the lagoon border located near Nador and utilized as the base for new buildings. Other solid residues derived from the Kariet Arkmane slaughterhouse are dumped directly into the lagoon.

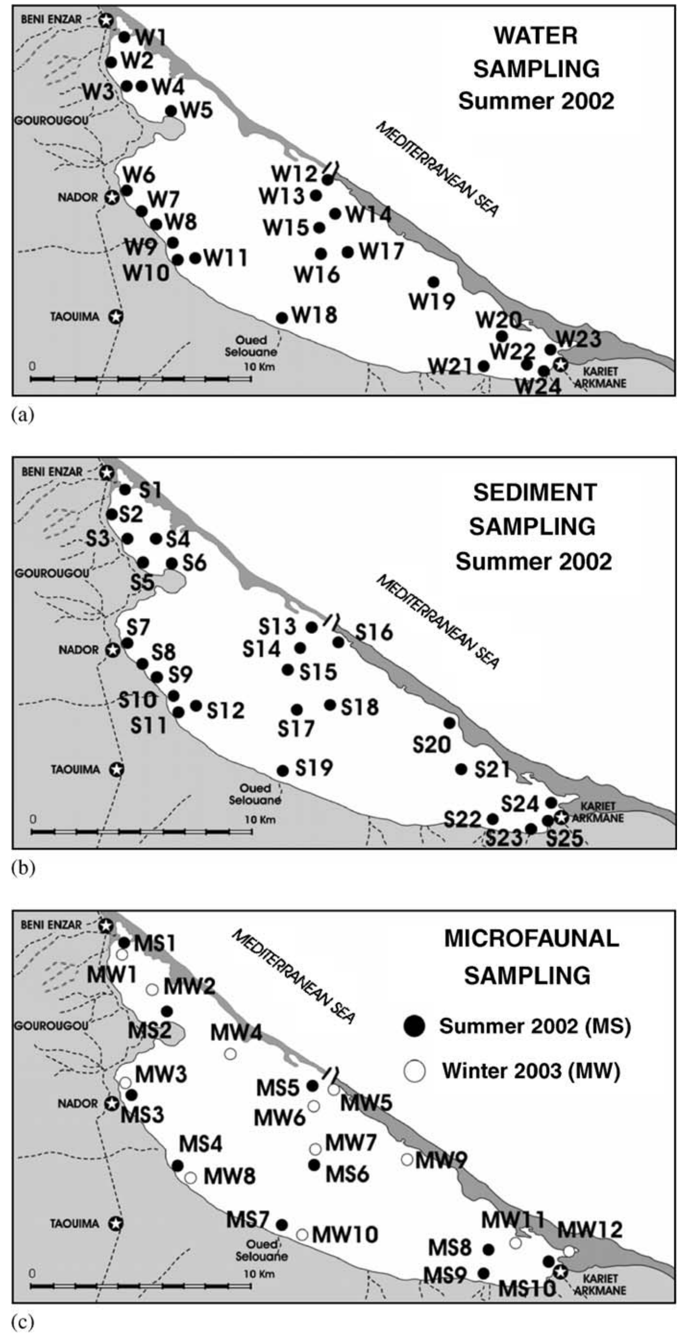



Fig. 2. Maps showing sampled sites for waters, sediments, and microfauna.

## 3. Methodology

### 3.1. Waters

Twenty-four samples were collected between 23 and 26 July 2002 (Fig. 2a) and subjected to the following procedures in the Surface Geochemical Centre (Strasbourg, France): analysis of some physical–chemical parameters (salinity and pH); ion chromatography (Dionex) for phosphates, nitrites, and sulfates; and colorimetry for ammonium. Results are expressed in mg/L.

### 3.2. Sediments

A sampling campaign was conducted in summer 2002 (Fig. 2b) to extract the bottom sediments of the Nador lagoon. Sediments were collected manually from the upper 2 cm of the bottom and frozen immediately. A fixed quantity of dried sediments (200 g) was wet sieved (2000, 1000, 500, 250, 125, and 63 μm mesh). The sedimentological results were compared with those obtained by Erimesco (1961) and Tesson (1977) in order to establish the grain-size distribution.

In addition, seven trace elements were determined (in mg/kg) on the <2 mm fraction using neutron activity analysis (Cd, Cu, Mn, Pb, Zn) and inductively coupled plasma-optical emission spectrometry (As, Co). Detection limit is 0.5 mg/kg, except for Mn (1 mg/kg) and Zn (0.3 mg/kg). The accuracy of the analytical procedures for metal determinations was checked using CRM 320 (sediment reference material), with recovery rates of heavy metals between 89% and 102%.

### 3.3. Micropaleontology

In summer 2002, 10 samples were selected for the analysis of the ostracod record present in the upper two centimeters of sediments (Fig. 2c), because these micro-crustaceans usually live near the water–sediment interface (Carbonel, 1980). In each sample, 100 g (dry weight) were first diluted with water for 48 h. Later, a mixture of calcium pyrophosphate, CALGON, hydrogen peroxide, and water was added during 48 h, with the periodical elimination of the bottom residues. The solution was slowly passed through a 63-μm sieve and the residues were passed to capsules of fireproof porcelain. The final residues are dried in an oven at 70 °C, collected into small plastic containers, and included in the micropaleontological inventory of the Huelva University (Spain). A similar procedure was used for 12 samples collected in winter 2003. The distribution of these samples is slightly different from that of those collected in summer 2002, but the two results can be compared and an approximation to the distribution of the main assemblages was made.

The total ostracod fauna was picked and included into slides, except if densities are very high (>1000 individuals per sample). In this case, approximately 500 individuals were picked, with a subsequent extrapolation to the whole sample. This number clearly exceeds the number of individuals (300) required for the statistical analysis of the ostracod assemblages (i.e., Ruiz et al., 1997). Both density (number of individuals per gram) and diversity (number of species) of each sample were calculated. Taxonomical identification keys were provided by Bonaduce et al. (1975), Llano (1981) and Athersuch et al. (1989).

### 3.4. Statistical procedure

In a first step, both water and sediment datasets were standardized; i.e., each variable has a mean of zero, being expressed by units of standard deviation. The Pearson correlation coefficient was calculated between the variables measured in each case and a clustering procedure is applied using a hierarchical agglomerative technique, with the application of the Euclidean distance. Outliers were defined according to the rescaled distance cluster combine (Figs. 4 and 6). All these operations were performed using SYSTAT 11.0.

Results derived from these multivariate analyses were compared with the distribution of the main ostracod associations. These associations are defined by one to three dominant species, well represented in most samples of the lagoon or dominant in an specific area of the lagoon, and some additional species, less abundant and expanded but important by their ecological significance.

## 4. Results

### 4.1. Waters

#### 4.1.1. Physical–chemical parameters and nutrients

The Nador Lagoon presents a salinity range typical of marine waters (38–39.5‰ in most cases), with higher values restricted to the confined areas located near Beni Ensar, to the northwest, and Kariet Arkmane, to the southeast. Consequently, the freshwater inputs coming from these two areas do not have a significant importance over this parameter, although these contributions increase clearly both the nutrient contents (nitrites: 0.018–0.024 mg/L; ammonium: even 0.008 mg/L) and the pH values (Fig. 3). On the contrary, the sulfate concentrations decrease (665–998 mg/L), mainly in the areas adjacent to the former town.

In the inner lagoon margin, salinity decreases slightly (<38‰) near the TSN, coinciding with high nutrient values (nitrites: 0.008–0.016 mg/L; phosphates: 0.003–0.004 mg/L; ammonium: 0.017–0.04 mg/L). These concentrations decrease near Nador, where only isolated high nitrite contents were found (0.016 mg/L).

In the remaining areas of the lagoon, salinity (37.6–38.2‰), pH (8.1–8.3 in most cases), nitrites (0.003 mg/L in most cases), phosphates (0.001 mg/L), sulfates (1450–1507 mg/L), and ammonium (0.001 mg/L) show very constant values.

#### 4.1.2. Statistical analysis

The Pearson matrix (Fig. 4a) reflects this distribution clearly, with a very significant correlation ($r = 0.596-0.758$; $P<0.01$) between the nutrient concentrations. In addition, a minor but still significant relation (pH–phosphates) was found, although the scarce variation found in the phosphate concentrations (0.001–0.004 mg/L) does not permit outlining a general relation between these two variables.

Three groups are identified in the cluster analysis (Fig. 4b). Cluster 1 is composed of three samples located very close to the TSN, which also presents high nutrient values and specially ammonium. These contents are lower in Cluster 2, which is composed of two samples located near Kariet Arkmane and a very shallow sample very close to Beni Enzar (Fig. 4c). Finally, Cluster 3 comprises the rest of the lagoon and may be considered as a local water background, owing to the smaller values for all variables measured in relation to the previous groups.

Samples W1 and W2 are ungrouped in this analysis. These confined samples are located between some oueds coming from the Gourougou massif and the fecal water

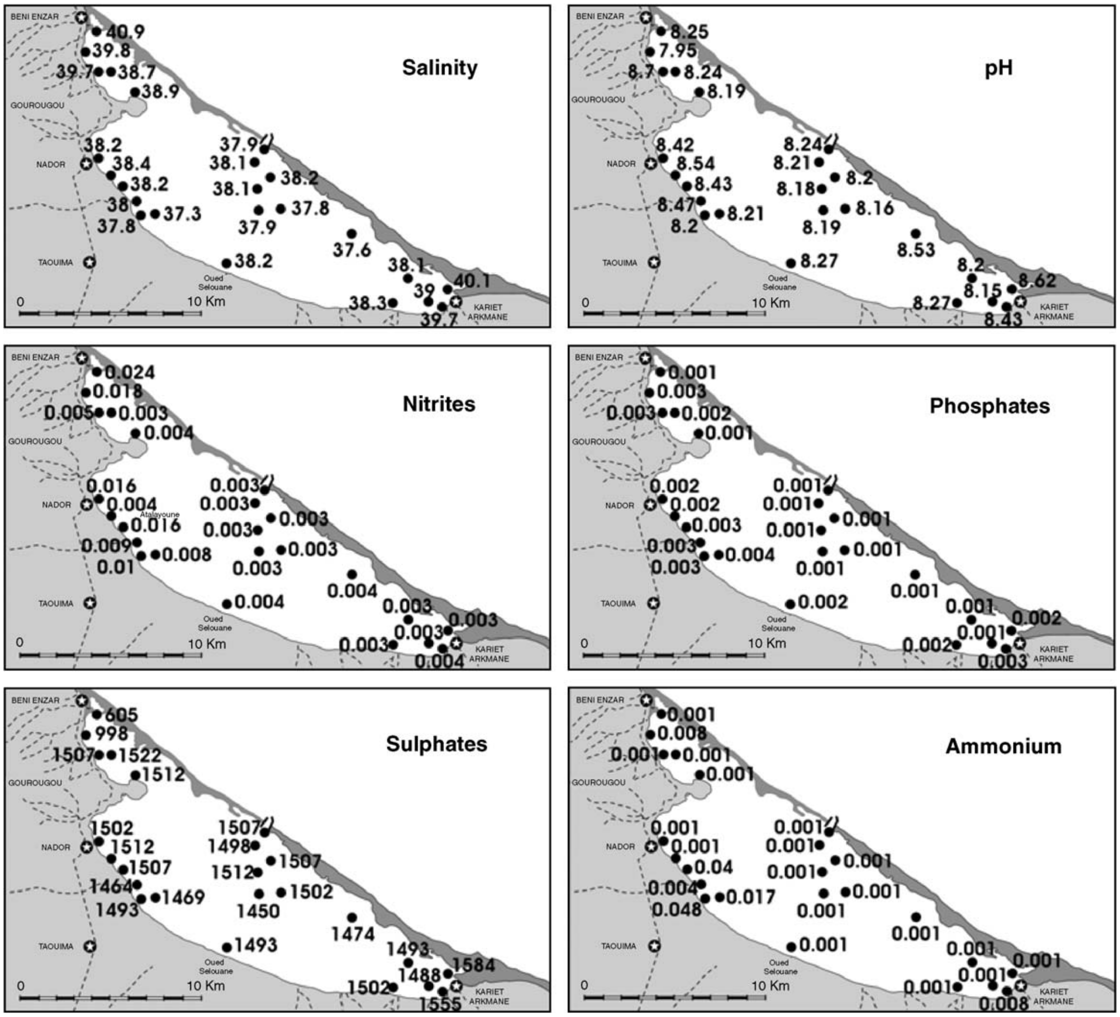



Fig. 3. Summer 2002. Physicochemical water parameters.

effluent of the Beni Enzar town. They are characterized by high salinities, normal to very high nutrient content and low sulfate concentrations.

### 4.2. Sediments

#### 4.2.1. Grain size

The grain size distribution of the bottom sediments shows a zoned pattern from the inner margin to the elongated sandy spit in a NW–SE direction (Fig. 5a). The continental margin consists mainly of black silts (mean: 20–60 μm) with numerous bioclasts, well sorted in the northwestern part (samples S2–S5) in relation to the southern border located between samples S7 and S22 where sands and gravels may be locally important (>30%) in some oued mouths. These sediments are replaced by well-sorted, very to very fine sands containing small bivalves (*Venerupis aurea*, *Venerupis decussatus*) near Beni Ensar and Kariet Arkmane.

The central, deeper area of the lagoon (samples S15, S17, and S18) is constituted by dark to green silty–clayey sediments with fragments of molluscs (*Cardium glaucum*, *Ostrea edulis*, *Venerupis* spp.). These fine sediments are progressively replaced by coarser grain sizes near the littoral spit (samples S13, S16 or S20), where very fine to medium sands (>75% dry weight) are dominant near the artificial inlet. In this zone, these sands contain numerous fragments of bivalves (*Anomia ephippium*, *Arca noae*, *Chlamys flexuosa*, *Mactra corallina corallina*) and gastropods (*Murex*, *Cerithium*). In contrast, black silts with numerous fragmented and eroded individuals of bivalves (*Glycymeris violacescens*, *Cardium glaucum*, *Venerupis decussatus*) and gastropods (*Architectonica*, *Murex*) characterize the southeastern inner side of this spit (i.e., sample S21).

#### 4.2.2. Heavy metals

A preliminary analysis detects an outlier (sample S6) located near an old iron mine. Heavy metal concentrations at this site are between 5 and 140 times higher than the rest of the lagoon for all metals studied (Figs. 5b–h) and

(a)

| | Salinity | pH | $NO_2^-$ | $PO_4^{3-}$ | $SO_4^{2-}$ | $NH_4^+$ |
|---|---|---|---|---|---|---|
| Salinity | 1 | | | | | |
| pH | 0.186 | 1 | | | | |
| $NO_2^-$ | 0.160 | 0.268 | 1 | | | |
| $PO_4^{3-}$ | 0.122 | 0.411* | 0.598** | 1 | | |
| $SO_4^{2-}$ | 0.307 | 0.300 | - 0.387 | 0.033 | 1 | |
| $NH_4^+$ | - 0.154 | 0.002 | 0.596** | 0.758** | - 0.205 | 1 |

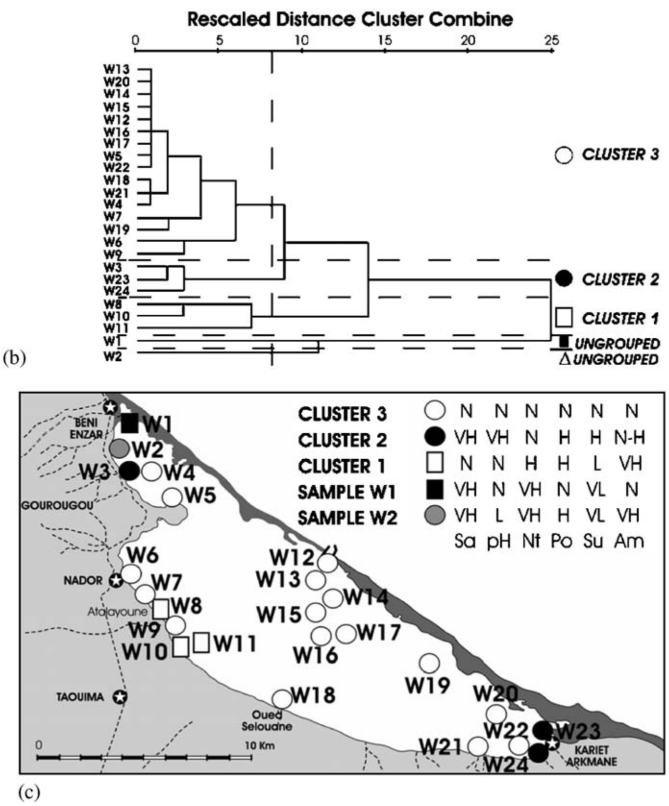



Fig. 4. Statistical analysis of the water database. (a) Pearson correlation matrix. $*P<0.05$; $**P<0.01$. (b) Cluster analysis. (c) Spatial location of the clusters obtained and comparison between their main water characteristics. Sa: salinity; Nt: nitrites; Po: phosphates; Su: sulphates; Am: ammonium. VL: very low; L: low; N: normal; H: high; VH: very high.

consequently it was removed from the subsequent statistical procedures.

A later revision of the spatial heavy metal distributions indicates the presence of a moderately polluted area situated between Nador and the TSN (Co: 15–24 mg/kg; Cu: 46–94 mg/kg; Mn: 558–826 mg/kg; Pb: 41–73 mg/kg; Zn: 140–212 mg/kg). The remaining samples present lower metal contents in most cases, especially from the artificial outlet to the east (i.e., Co: 5–12 mg/kg; Cu: 13–47 mg/kg; Pb: 0–43 mg/kg; Zn: 40–103 mg/kg), whereas intermediate values between these two zones were observed near the northwestern continental margin for most metals. Low to very low polluted sediments were found near the fecal water effluent of Beni Enzar and close to the artificial inlet.

#### 4.2.3. Statistical analysis

The Pearson matrix shows a clear heavy metal association composed of Co, Cu, Mn, Pb, and Zn (Fig. 6a: $r = 0.568-0.863$; $P<0.01$), with a minor but still significant correlation of some of these metals with Cd. The As contents do not have any lineal relation with the rest of heavy metals.

The cluster analysis makes it possible to define four clusters and three ungrouped samples (S2, S3, and S13). The former association is especially abundant between Nador and TSN (Figs. 4b and c: Clusters A and C), whereas very low contents are found in the sediments collected near some freshwater inputs (Cluster B). Finally, Cluster D includes 12 samples with low to very low pollution levels.

Sample S13 is located near the artificial outlet and is characterized by high As concentrations and low contents of the former association. Very variable values are typical of the northwestern continental margin (Samples S2 and S3).

### 4.3. Ostracods

#### 4.3.1. Summer 2002

Thirty-nine species were determined in the study of the 1987 individuals picked from more than 4300 individuals calculated by linear extrapolation. Both diversity and density are very variable in the samples and consequently a detailed analysis of the different parts of the lagoon is necessary.

Ostracods make it possible to differentiate two areas in the northwestern confined zone of the lagoon. These microorganisms are abundant (>28 individuals/g) and poorly diversified (6 species) near the fecal water effluent of Beni Ensar town (Table 1). *Cyprideis torosa* is dominant (92%; 26 individuals/g), with *Aurila woodwardii* (4.6%) and *Loxoconcha rhomboidea* (2%) as secondary species. The ostracod age structure of *Cyprideis torosa* shows a notorious predominance of instars (72.8%) on the adults (27.2%). In contrast, they are absent in the polluted sediments located near the old iron mine.

Low densities and moderate diversities (1.5–3.3 individuals/g; 11–18 species) were found in the inner lagoon margin located between the Atalayoum promontory and Kariet Arkmane. The main assemblage of this area is composed by *Loxoconcha rhomboidea* (39–51%; 67–160 individuals/100 g), *Palmoconcha turbida* (2–26.7%; 4–105 individuals/100 g) and *Cyprideis torosa* (4–23%; 10–67 individuals/100 g), with *Aglaiocypris complanata*, *Leptocythere lagunae*, and *Cytherois fischeri* as secondary species. On the southeastern border of the lagoon (Kariat Arkmane), only adult specimens of *Loxoconcha rhomboidea* and instars of *Cyprideis torosa* were found. An exception was found in the mouth of the Oued Selouane,

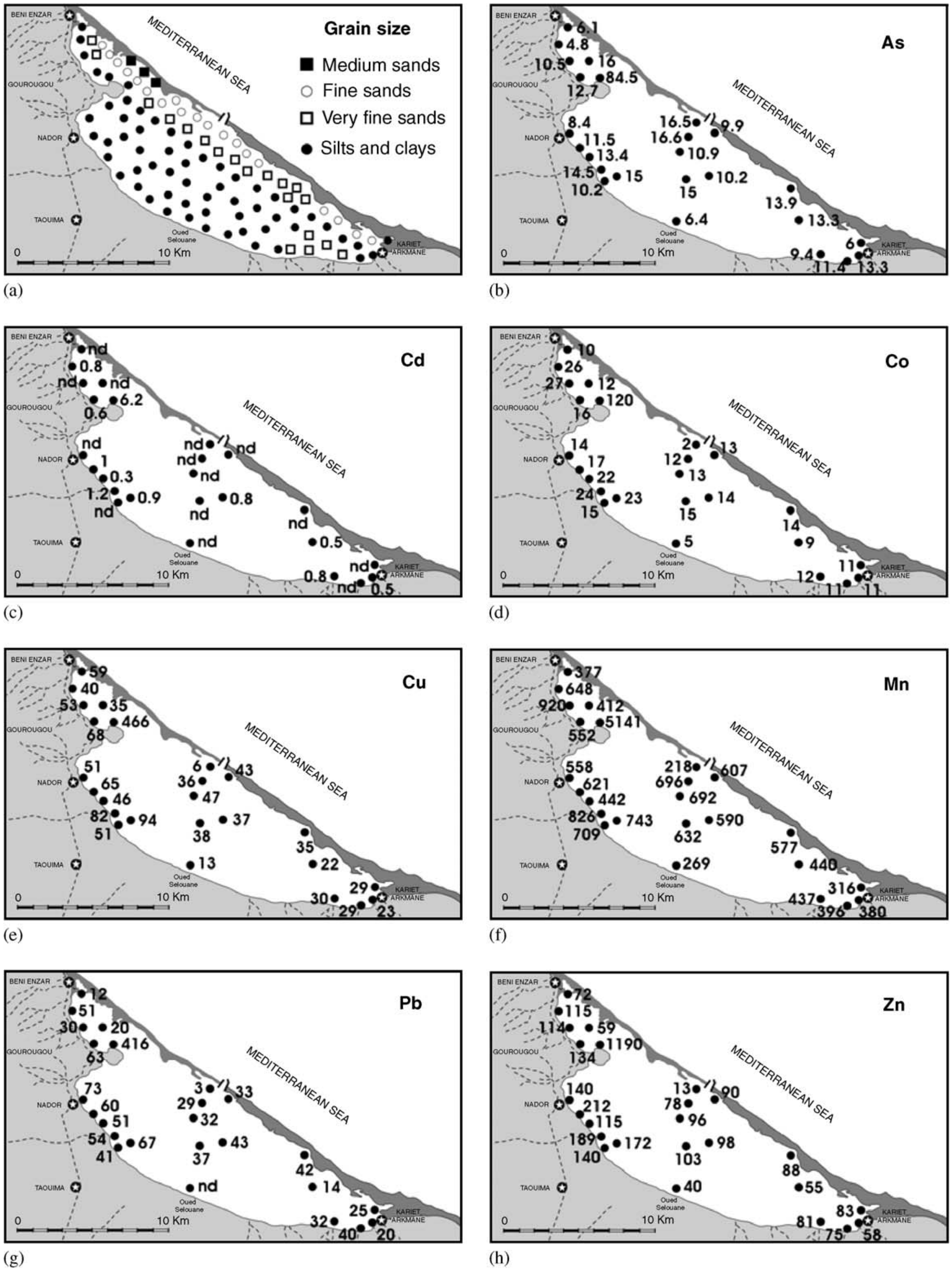


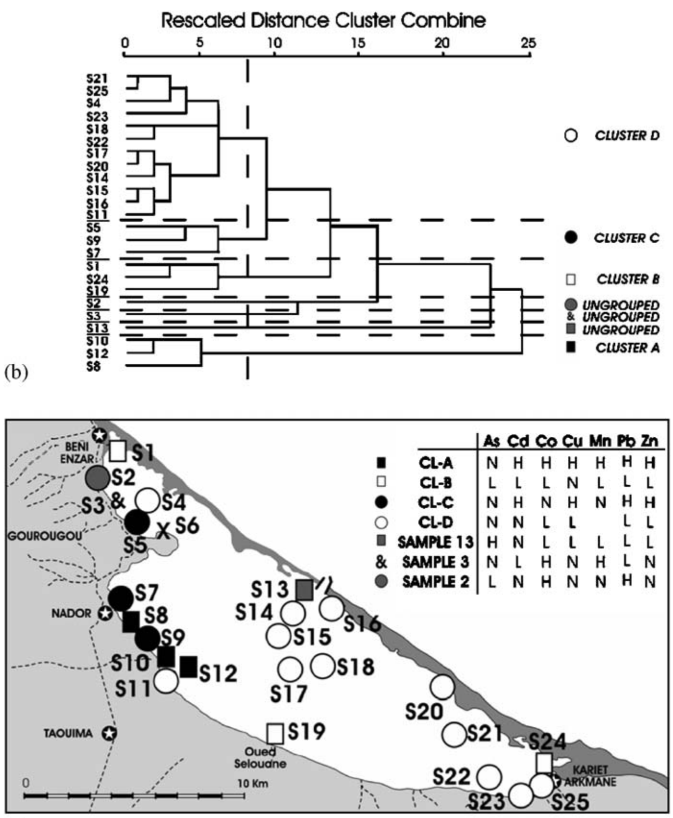

Fig. 5. Grain size (a) and heavy metal contents (b–h; in mg/kg) of the Nador lagoon.

where no ostracods were observed in this sampling campaign (Figs. 7a and b).

The southeastern central area presents the higher diversities of the lagoon (sample MS8: 32 species), with *Loxoconcha rhomboidea* (~25%), *Propontocypris frequens* (18%), *Leptocythere lagunae*, and *Cyprideis torosa* as more representative species. In contrast, density is very low (9 individuals/100 g) in the deeper central area, where adults of *Loxoconcha rhomboidea* and instars of *Cyprideis torosa* have been found together. This scarcity was also found near the artificial inlet, where the ostracod faunas are represented mainly by reworked specimens of *Cyprideis*

| | As | Cd | Co | Cu | Mn | Pb | Zn |
|---|---|---|---|---|---|---|---|
| As | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Cd | 0.055 | 1 | | | | | |
| Co | -0.031 | 0.466* | 1 | | | | |
| Cu | 0.072 | 0.480* | 0.701** | 1 | | | |
| Mn | 0.114 | 0.281 | 0.778** | 0.681** | 1 | | |
| Pb | 0.042 | 0.476* | 0.675** | 0.727** | 0.568** | 1 | |
| Zn | 0.001 | 0.579** | 0.727** | 0.863** | 0.693** | 0.850** | 1 |

(a)




(c)

Fig. 6. Statistical analysis of the sediment database. (a) Pearson correlation matrix. $*P<0.05$; $**P<0.01$. (b) Cluster analysis. (c) Spatial location of the clusters obtained and comparison between their main heavy metal contents. L: low; N: normal; H: high; VH: very high.

*torosa* (all adults) and isolated instars of *Cytheretta adriatica* and *Pontocythere turbida*.

#### 4.3.2. Winter 2003

The 3304 individuals picked (of 5964 individuals calculated) belong to 48 species (Table 2). These micro-organisms are also very abundant near Beni Enzar during this station, with a strong dominance of *Cyprideis torosa* (>95%; >10 individuals/g) and minor contributions of *Loxoconcha rhomboidea*. The central part of this confined area shows now the presence of reworked freshwater species (*Cypridopsis vidua*), probably coming from the adjacent small streams.

In the inner lagoon margin, these crustaceans are absent from northern Nador (Figs. 7c and d: sample MW3). Both densities (2–3.4 individuals/g) and diversities (6–8 species) are low between Nador and the Selouane oued. The ostracod assemblage is dominated by *Loxoconcha rhomboidea* (64–71%; 132–239 individuals/100 g), with minor contributions of *Cyprideis torosa*, *Propontocypris declivis/pirifera*, and *Palmoconcha turbida*. In the southeastern, more confined part of the lagoon, ostracods are poorly developed, with scarce adult individuals of *Cyprideis torosa* and *Aurila woodwardii*.

*Cyprideis torosa* and *Pontocythere turbida* are dominant in the low diversified ostracod assemblage (7 species; ~2 individuals/g) observed in the moderately deep areas of the central lagoon, with *Cytherois fischeri* and *Leptocythere fabaeformis* as additional species. The most abundant (14.8–18.4 individuals/g) and diversified (13–38 species) ostracod assemblages of the lagoon during this station are located between this area and the sandy spit. *Pontocythere turbida*, *Cyprideis torosa*, *Xestoleberis communis*, *Palmoconcha turbida*, and *Loxoconcha rhomboidea* are the main species of these silty–sandy sediments. An exception was found in the artificial lagoon mouth, where ostracods are absent.

## 5. Discussion

### 5.1. Comparison with other northern African and European coastal areas

#### 5.1.1. Waters

In the Nador Lagoon, most of the water variables show values similar to those measured in unpolluted marine waters of other coastal Moroccan environments (review in Table 3). These data suggest a strong dominance of the tidal, marine inputs over the different freshwater inputs (fecal waters, urban effluents, treated waters, slaughterhouse) detected along the lagoon margin. Salinities are slightly higher (>40‰) in the two more confined areas of the lagoon located near Beni Enzar and Kariet Arkmane, characterized by shallow waters (~1 m depth), very low tidal renewal (Tesson, 1977), and high sedimentation ratios (0.41 cm/yr near this last locality; Bellucci et al., 2003). All these features indicate an increasing filling process in these areas and they are also found in other northern African coastal lagoons where there is a present transition toward a sabkha scenario (i.e., El Meleh lagoon, Tunisia; Ruiz et al., 2004b).

These freshwater inputs induce only a very small increase in the nutrient content near these sites, whereas a strong decrease of the sulfate concentrations (600–1000 mg/L) was found near Beni Enzar in relation to other coastal Moroccan waters (~1300–1500 mg/L; Cheggour et al., 2005). These effects should suggest a more pronounced effect of its fecal water effluent on the adjacent areas in relation to the slaughterhouse-derived wastes and urban sewage of Kariet Arkmane during the summer, although

Table 1
Summer 2002: abundance and diversity of ostracods in the Nador Lagoon

| Species samples | MS1 | MS3 | MS4 | MS5 | MS6 | MS8 | MS9 | MS10 |
|---|---|---|---|---|---|---|---|---|
| *Aglaiocypris complanata* | | | 15 | | | 32 | 21 | |
| *Aurila convexa* | | | 2 | | | 1 | | |
| *Aurila woodwardii* | 128 | 15 | 3 | | | 2 | | |
| *Callistocythere lobiancoi* | | 1 | | | | 22 | 3 | |
| *Callistocythere* sp. | | | | | | 1 | | |
| *Carinocythereis whitei* | | 4 | | | | | | |
| *Cyprideis torosa* | 2603 | 38 | 67 | 7 | 25 | 45 | 10 | 31 |
| *Cytheretta adriatica* | 6 | | | 1 | | 12 | | |
| *Cytherois fischeri* | | | 7 | | 9 | 6 | 6 | |
| *Cytheroma variabilis* | | | | | 2 | 8 | 2 | |
| *Hiltermannicythere rubra* | 11 | | | | | | | |
| *Leptocythere castanea* | | 4 | | | | 10 | 19 | |
| *Leptocythere lagunae* | 20 | 19 | 17 | | | 49 | 9 | |
| *Leptocythere rara* | | | 4 | | | 1 | | |
| *Leptocythere* sp. | | | | | | 2 | | |
| *Loculicytheretta pavonia* | | | | | | 7 | | |
| *Loxoconcha elliptica* | | | 2 | | | | 1 | |
| *Loxoconcha rhomboidea* | 55 | 67 | 160 | | 5 | 141 | 126 | 64 |
| *Neocytherideis subulata* | | | | | | 6 | | |
| *Palmoconcha turbida* | | 4 | 105 | | 4 | 23 | 27 | |
| *Paracypris polita* | | | | | | 1 | | |
| *Paracytheridea depressa* | | | | | | 2 | | |
| *Paradoxostoma taeniatum* | | | | | | | 2 | |
| *Pontocythere turbida* | | | | 1 | | 2 | | |
| *Propontocypris frequens?* | | | | | | 101 | 4 | |
| *Propontocypris* cf. *P. levis* | | | | | | | 1 | |
| *Pseudopsammocythere similis* | | | | | | 2 | | |
| *Sagmatocythere napoliana* | | | | | | 3 | | |
| *Semicytherura incongruens* | | | | | | 8 | 6 | 2 |
| *Semicytherura sulcata* | | | | | | 11 | 1 | |
| *Semicytherura* cf. *S. robusta* | | | | | | 1 | | |
| *Semicytherura* sp. 1 | | | | | | | 1 | |
| *Urocythereis margatirifera* | | | | | | 6 | 1 | |
| *Urocythereis oblonga* | | | | | | 3 | | |
| *Xestoleberis communis* | | 3 | | | | 8 | 1 | |
| *Xestoleberis decipiens* | | | 2 | | | | | |
| *Xestoleberis depressa* | | | | | | 10 | | |
| *Xestoleberis plana* | | | | | | 30 | | |
| *Xestoleberis* sp. | | | | | | 2 | | |

this situation is inverse if the mean daily inputs are considered during a complete year (Beni Enzar: 2250 $m^3$/day; Kariet Arkmane: 5728 $m^3$/day; Dakki et al., 2003). In addition, both zones show locally high pH values ($>8.5$) due to the absence of freshwater inputs during this dry season (Inani, 1995).

Near the TSN, the nutrient contents are also over the mean lagoon values (mainly ammonium), although always with very low absolute values ($<0.05$ mg/L) in relation to some Moroccan phosphore factory effluents (mean 8.72 mg/L; Kaimoussi et al., 2001). In this area, the $O_2$ dissolved contents are very low (3.9 mg/L) in summer in comparison with the marine influence area close to the artificial inlet (10.5 mg/L), owing to the organic matter consumption (Inani, 1995).

In the central and external areas of the lagoon, both salinity and pH values are very similar to those detected in other Moroccan coastal waters not subject to human-induced inputs (i.e., El Jadida city or Jorf Lasfar; Kaimoussi et al., 2001, 2002). Nutrient contents are even lower than those measured in these unpolluted areas.

### 5.1.2. *Heavy metal pollution*

A comparison with the metal contents measured in other northern African coastal areas shows the strong impact of the old iron mine located in the Atalayoum promontory on the adjacent bottom sediments. In this sector, the use of a tailing pond system and the absence of environmental controls have caused the presence of metal levels similar to the lowest value ranges observed in very polluted estuarine systems (i.e., Tinto-Odiel estuary; Ruiz, 2001) and makes it possible to classify him between the most contaminated areas of northern Africa (see Table 3).

The coastal section comprised between Nador and the TSN has both Cu and Pb concentrations slightly higher than some Moroccan low-polluted estuaries, whereas it is

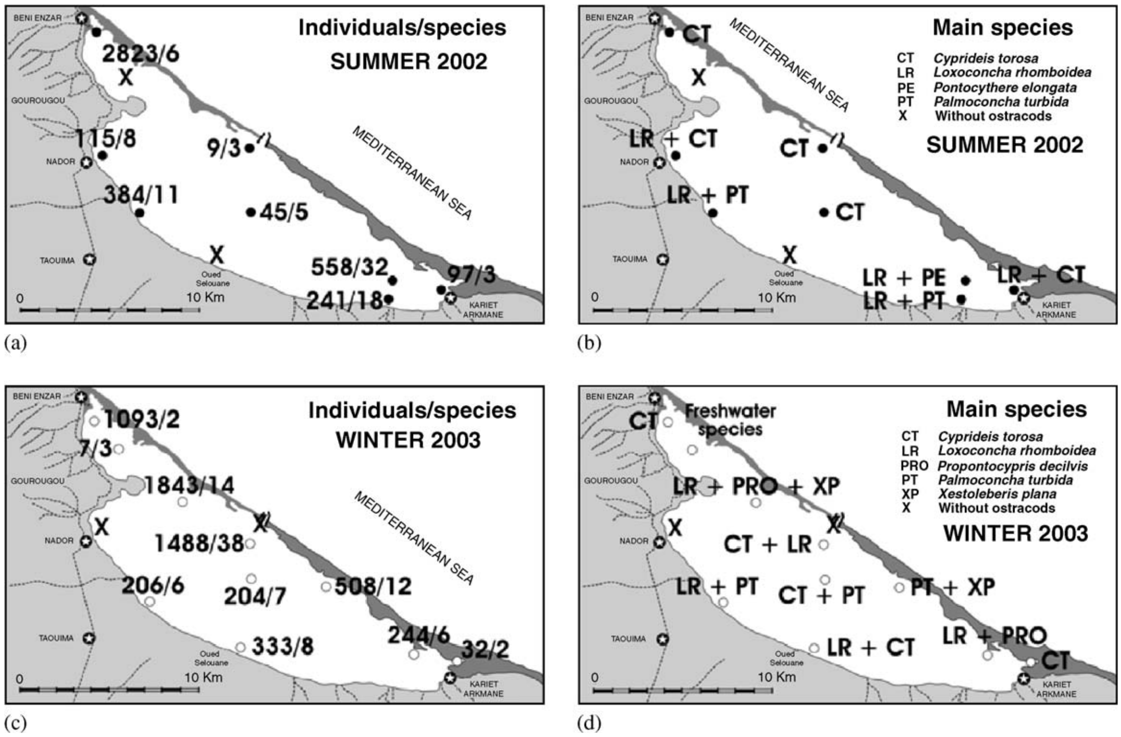



Fig. 7. Abundance, diversity, and distribution of the main ostracod species in the El Nador lagoon. (a, b) Summer 2002; (c, d) winter 2003.

remarkable the presence of Mn contents two to four times larger than those observed in these areas (Cheggour et al., 2005). This moderate pollution may be due to the tailing pond system used in the TSN, which permits a flow of heavy metals to the lagoon.

The rest of the lagoon presents very low polluted sediments, with heavy metal concentrations close to those measured in other Moroccan lagoons with scarce agricultural inputs (Cheggour et al., 2001).

### 5.2. *Ostracods as biomonitors*

#### 5.2.1. *Ostracod autoecology*

Three main groups of ostracods may be distinguished between the most abundant species collected:

(a) Freshwater to low brackish water assemblage: *Cypridopsis vidua*. This species is frequent in stagnant warm waters with bottom vegetation, tidal marshes, coastal ponds, lakes, irrigation ditches, temporary freshwater streams or springs with very low salinity values (Bronshtein, 1988; Meisch, 1987). A few individuals were only found in the central part of the northwestern confined area during the winter campaign, which can be transported by the freshwater flows coming from the adjacent oueds.

(b) High brackish water assemblage: *Cyprideis torosa* (smooth ornamentation), *Cytherois fischeri*, *Leptocythere castanea*, *Leptocythere lagunae*, and *Loxoconcha elliptica*. These species characterize the inner, shallow areas of recent peri-Mediterranean lagoons with marine connection (Marocco et al., 1996; Montenegro and Pugliese, 1996; Ruiz et al., 2000a). More specifically, two of them (*Cyprideis torosa* and *Loxoconcha elliptica*) are clearly associated with all the different transitional environments between fresh and marine waters with strong tropic gradients and high salinity variability (Carbonel, 1982). In summer, this assemblage is especially abundant near the Beni Enzar effluent and the deeper areas of the lagoon, whereas *Cyprideis torosa* becomes also dominant near Kariet Arkmane.

(c) Marine assemblage: *Aurila woodwardii*, *Carinocythereis whitei*, *Cytheretta adriatica*, *Hiltermannicythere turbida*, *Loxoconcha rhomboidea*, *Neocytherideis subulata*, *Palmoconcha turbida*, *Propontocypris frequens*, *Semicytherura acuticostata*, *Semicytherura incongruens*, and *Xestoleberis communis*. All these species are frequent in the North African and southwestern Spanish shallow marine waters, although they have different environmental significance. *Carinocythereis whitei*, *Cytheretta adriatica*, *Hiltermannicythere turbida*, and *Neocytherideis fasciata* are coastal, nonphytal species, which may live together with some coastal opportunistic taxa (*Aurila woodwardii*, *Palmoconcha turbida*, *Semicytherura incongruens*). Others species (*Loxoconcha rhomboidea*, *Xestoleberis communis*) are also opportunistic but ubiquitous in all the littoral environments. These former species live mainly in the upper 2–3 cm of the bottom sediments, whereas *Propontocypris frequens* can swim short distances and it was found mainly between calcareous algae. A more detailed review may be

Table 2
Winter 2003: abundance and diversity of ostracods in the Nador Lagoon

| Species samples | MW1 | MW2 | MW4 | MW6 | MW7 | MW8 | MW9 | MW10 | MW11 | MW12 |
|---|---|---|---|---|---|---|---|---|---|---|
| *Aglaiocypris complanata* | | | | 9 | | | | | | |
| *Argilloecia robusta* | | | 19 | | | | | | | |
| *Aurila woodwardii* | | | 22 | 11 | | 14 | 16 | 19 | 12 | 13 |
| *Bairdia longivaginata* | | | | 1 | | | | | | |
| *Callistocythere flavidofusca* | | | | | | | 14 | | | |
| *Carinocythereis carinata* | | | | 1 | | | | | | |
| *Carinocythereis whitei* | | | | 15 | 2 | | | | | |
| *Cyprideis torosa* | 1040 | | | 431 | 74 | 18 | | 42 | | 19 |
| *Cypridopsis vidua* | | 4 | | | | | | | | |
| *Cytheretta adriatica* | | | | 102 | | | 9 | | | |
| *Cytherois fischeri* | | | 20 | 67 | 32 | | | | | |
| *Hemicytherura videns* | | | | 9 | | | | | | |
| *Heterocythereis albomaculata* | | | | 1 | | | | | | |
| *Hiltermannicythere rubra* | | | | 8 | | | | | | |
| *Hiltermannicythere turbida* | | | | 43 | | | | | | |
| *Leptocythere castanea* | | | | | | | 11 | 1 | | |
| *Leptocythere fabaeformis* | | | 1 | 3 | 11 | | 28 | 4 | 5 | |
| *Leptocythere macallana* | | | | 25 | | | | | | |
| *Leptocythere rara* | | | | | | 1 | 1 | | | |
| *Loculicytheretta pavonia* | | | | 7 | | | | | | |
| *Loxoconcha elliptica* | | 1 | | | | | 11 | | 1 | |
| *Loxoconcha rhomboidea* | 53 | | 682 | 185 | 19 | 132 | 77 | 239 | 124 | |
| *Loxoconcha rubritincta* | | | | 13 | | | | | | |
| *Loxoconcha tumida* | | | 19 | 2 | | | | 3 | | |
| *Neocytherideis subulata* | | | | 47 | | | | | | |
| *Palmoconcha turbida* | | | 9 | 70 | | 40 | 138 | | 10 | |
| *Paracytheridea depressa* | | | | 3 | | | | | | |
| *Phlyctocythere pellucida* | | | | 5 | | | | | | |
| *Pontocypris trigonella* | | | | 1 | | | | | | |
| *Pontocythere turbida* | | | 27 | | 85 | | | | | |
| *Propontocypris declivis* | | | 440 | | | 1 | 85 | 11 | 92 | |
| *Quadracythere* sp. | | | | 1 | | | | | | |
| *Ruggieria tetraptera* | | | | | 1 | | | | | |
| *Sagmatocythere napoliana* | | | 6 | 8 | | | 1 | | | |
| *Sagmatocythere versicolor* | | | | 14 | | | | | | |
| *Sahnicythere retroflexa* | | | | 25 | | | | | | |
| *Semicytherura acuticostata* | | | | 19 | | | | | | |
| *Semicytherura incongruens* | | | 1 | | | | | | | |
| *Semicytherura sulcata* | | | 14 | 74 | | | 1 | | | |
| *Semicytherura trachina* | | | | 1 | | | | | | |
| *Semicytherura* cf. *S. inversa* | | | | 1 | | | | | | |
| *Semicytherura* cf. *S. sella* | | | | 39 | | | | | | |
| *Triebelina raripila* | | | | 1 | | | | | | |
| *Urocythereis margatirifera* | | | | 1 | | | | | | |
| *Urocythereis oblonga* | | | | 55 | | | | | | |
| *Xestoleberis communis* | | | | 136 | | | 2 | 14 | | |
| *Xestoleberis plana* | | 2 | 578 | 54 | | | 114 | | | |
| *Xestoleberis* sp. | | | | 11 | | | | | | |

consulted in Lachenal (1989), Llano (1981), Ruiz et al. (2000b), and Yassini (1979).

The nonphytal species are most abundant near the artificial inlet, whereas the opportunistic taxa may be even dominant in the inner areas of the lagoon, close to the TSN.

### 5.2.2. Ostracods as environmental biomonitors

Ostracods can be used as biomonitors of the environmental conditions present in the different areas of the lagoon. In the northwestern confined area, the high brackish ostracod assemblage is abundant (>10 individuals/g), constituted almost monospecifically by *Cyprideis torosa* near the fecal water effluent of Beni Enzar. High abundances of *Cyprideis* (>300 individuals/g in some cases) are frequent in numerous coastal lagoons of Africa and Europe (Carbonel, 1980; Carbonel and Pinson, 1982). This may be explained because this species is more frequent in quiet water environments, whereas *Loxoconcha elliptica* prefers higher hydrodynamic levels (Carbonel, 1980; Ruiz et al., 2000b). In the natural filling of coastal lagoons, the

Table 3
Comparison of the water and sediment qualities between lagoons and estuaries of Morocco, North Africa, and South Spain

| | Sites | Waters | | | | | | Sediments | | | | | | Observations | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Salinity | pH | Nitrites | Phosphates | Sulphates | Ammonium | As | Cd | Cu | Mn | Pb | Zn | | |
| Morocco | Nador | 37.3–40.9 | 7.95–8.7 | 0.003–0.024 | 0.001-0.004 | 605–1584 | 0.001–0.048 | 6.1–84.5 | 0–6.2 | 6–466 | 218–5141 | 3–416 | 13–1190 | Mining activities, treatment station, urban wastes | This paper |
| | El Jadida city (a) | nd | 7.43–7.71 | nd | 3.2–4.9 | nd | 39—76 | nd | nd | nd | nd | nd | nd | Urban discharges | Kaimoussi et al., 2002 |
| | El Jadida city (b) | 21.18–34.95 | 7.03–8.5 | 0.003–0.160 | 0.001–2.72 | nd | nd | nd | nd | nd | nd | nd | nd | Adjacent coastal zone | Kaimoussi et al., 2002 |
| | Jorf Lasfar (a) | nd | Mean 1.87 | nd | Mean 54.95 | nd | Mean 8.72 | nd | nd | nd | nd | nd | nd | Phosphore factory effluent | Kaimoussi et al., 2001 |
| | Jorf Lasfar (b) | 26.57–34.85 | 7.02–8.31 | 0.001-0.02 | 0.615–9.731 | nd | nd | nd | nd | nd | nd | nd | nd | Adjacent coastal zone | Kaimoussi et al., 2001 |
| | Gharb Plain | nd | ~5.2–9 | ~0–2.2 | ~0–4 | ~50–1500 | ~0.01–0.19 | nd | nd | nd | nd | nd | nd | Urban and industrial sewages | Bennaser et al., 1997 |
| | Loukkos Estuary | 25.8±3 | 8±0.1 | nd | nd | nd | nd | nd | 0.9–2.17 | 24–42 | 36.5–88.7 | nd | 116–142 | Agriculture, industries, harboractivity | Cheggour et al., 2005 |
| | Sebou Estuary | 26.8±2.7 | 7.6±0.1 | nd | nd | nd | nd | nd | 1.5–3.1 | 38–66 | 86.7–250 | nd | 150–206 | Agriculture, industries | Cheggour et al., 2005 |
| | Bou Regreg Estuary | 29.5±1.3 | 7.9±0.1 | nd | nd | nd | nd | nd | 1.1–3.0 | 32–56 | 109.5–200 | nd | 150–186 | Agriculture, handcraft activities, industries, fishing | Cheggour et al., 2005 |
| | Oumer Rbia Estuary | 26.0±2.1 | 8±0.1 | nd | nd | nd | nd | nd | 2–3.3 | 28–40 | 48.4–165.3 | nd | 150–186 | Agriculture, industries, fishing | Cheggour et al., 2005 |
| | Moulay Bou Selham lagoon | nd | nd | nd | nd | nd | nd | nd | 0.6–1.5 | 25.5–40 | nd | 13.5–30.9 | 87–170 | Agriculture, aquaculture, fishing, tourist activities | Cheggour et al., 2001 |
| | Sidi Moussa lagoon | nd | nd | nd | nd | nd | nd | nd | 3–4.7 | 29.5–41.8 | nd | 25.2–40 | 73–185 | Agriculture | Cheggour et al., 2001 |
| | Sidi Moussa lagoon | nd | nd | nd | nd | nd | nd | nd | nd | 20–42 | nd | nd | 19–73 | Agriculture | Maanan et al., 2004 |
| | Oualidia lagoon | nd | nd | nd | nd | nd | nd | nd | ~50–1500 | ~2–37 | nd | ~5–25 | ~5–100 | Agriculture | Bidet and Carruesco, 1982 |
| Northern Africa | Algiers Bay, Algeria | nd | nd | nd | nd | nd | nd | nd | nd | 6–96 | nd | 2–77 | 52–291 | Industrial wastes, harbour | Benamar et al., 1999 |
| | Eastern Libyan coastline | nd | nd | nd | nd | nd | nd | nd | <1–1.73 | 8.7–42 | 37–76.7 | nd | 2.3–27.3 | Harbours | Hamouda and Wilson, 1989 |
| | El Meleh lagoon, Tunisia | 5.9–40.3 | 6.3–8.5 | 0.005–0.115 | 0.06–1.99 | nd | 0.006–0.36 | 3.3–18.8 | 0–4.5 | 0–29 | 112–365 | 0–38 | 14–105 | Treatment station | Ruiz et al., 2004b |
| | Manzalah lagoon, Egypt | 1.38–2.88 | 6.91–9.47 | 0.004–0.0476 | 0.030–0.163 | nd | nd | nd | 3.7–17.9 | 34.4–117 | nd | 43.5–122.9 | 94.6–239.7 | Industrial, agricultural and municipal sewages | Samir, 2000 |
| | Edku lagoon, Egypt | 1.1–2.11 | 7.74–9.02 | 4.9–204 | 0.009-0.84 | nd | nd | nd | 0.5–0.9 | 1.8–2.1 | nd | 4.2–7.3 | 0.4–11.3 | Agricultural drainage | Samir, 2000 |
| Spain | Tinto-Odiel estuary | 22.8–35.3 | 6–8.2 | nd | nd | nd | nd | 12–850 | <1–9 | 25–2990 | nd | 11–4860 | 58–3330 | Historical mining, industrial wastes | Ruiz, 1994, 2001; Morillo et al., 2005 |

diminution of the hydrodynamic gradient and the presence of higher salinities cause the progressive replacement of *Loxoconcha elliptica* by *Cyprideis torosa*, which become almost monospecific (i.e., Bidet and Carruesco, 1982).

In the southeastern corner, there is a more confined and restricted area, located near Kariet Arkmane. A drastic diminution of this high-brackish assemblage was found in comparison with the previous zone, which may be caused by the increasing subaerial exposure of this margin with high sedimentation ratios (Bellucci et al., 2003). These two factors constitute a very unfavorable combination for ostracod development (Carbonel, 1980).

The adjacent areas close to the Atalayoum iron mine, the TSN and the artificial inlet show conditions even more stressing for these microcrustaceans (Fig. 8). In the first case, these microcrustaceans are absent in the highly polluted bottom sediments, as it was found in other coastal environments subjected to mining sewages and/or industrial discharges (Pascual et al., 2002; Ruiz et al., 2004a). Near the TSN, the coastal opportunistic species are dominant, being represented by taxa belonging to the Loxoconchidae family. *Palmoconcha turbida* and some species of *Loxoconcha* have high tolerances to low oxygen conditions derived from urban and/or agricultural inputs and may be the only taxa present or represent a high proportion of the total ostracod assemblages in hypoxic environments (Álvarez Zarikian et al., 2000; Bodergat et al., 1998). Ostracods are very scarce or absent near the artificial inlet, which present the highest bottom-water velocities of the lagoon (Inani, 1995), causing probably a bypassing of the bottom sediments and consequently a new stress situation for these microorganisms that live mainly near the water–sediment interface. Very low densities and diversities have been also found in other lagoon inlets or estuarine mouths (Carbonel, 1980; Ruiz et al., 2004b).

In the remaining, low-polluted areas of the lagoon, *Cyprideis torosa* is dominant in the quiet, central areas of the lagoon (6–7 m depth), which is accompanied by opportunistic species (mainly Loxoconchidae) in the intermediate zones (3–5 m) and on the southern margin. These unpolluted areas present moderate to high densities and diversities and can be representative of the natural conditions of this lagoon. Low agricultural wastes (i.e., local inputs of pesticides) do not significantly harm the ostracod communities (Samir, 2000).

## 6. Conclusions

The analysis of the water parameters, the heavy metal contents of the bottom sediments, and the ostracod faunas makes it possible to approximate the present environmental scenario of the Nador lagoon. Three main freshwater inputs (fecal water effluent of Beni Enzar, treatment station of Nador, and urban and slaughterhouse wastes of Kariet Arkmane) cause an enrichment in nutrients (mainly nitrogen compounds) in the adjacent waters, although they are slightly significant in relation to the main marine inputs and only cause a moderate hypoxic condition near the treatment station of Nador. Sediments show a clear spatial zonation from the silty–clayey bottoms located near the inner continental margin to the very fine, fine, and even medium sands observed near the external sandy spit. These sediments have high heavy metal concentrations near the old iron mine of the Atalayoum promontory, whereas the low mean values of the lagoon for As, Cd, Pb, and Zn are only surpassed near the treatment station of Nador in the rest of the lagoon.

In addition, these anthropogenic impacts cause some measurable changes of ostracod richness indices and produce the presence of specific assemblages or the apparition of opportunistic species under special conditions. High heavy metal pollution, hypoxic conditions, and high hydrodynamic levels induce the disappearance of these microcrustaceans, whereas an increasing subaerial

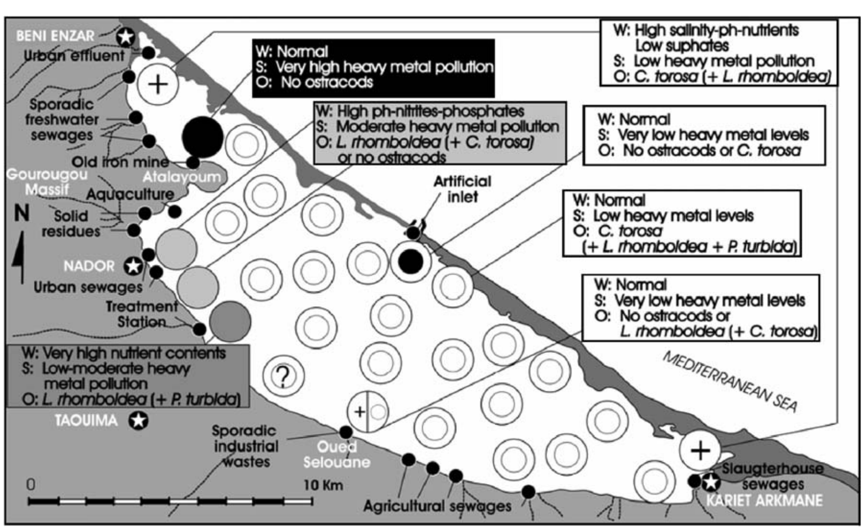



Fig. 8. An approximation to the present environmental scenario of Nador lagoon, with indication of the main features of each zone. (W) waters; (S) sediments; (O) ostracod assemblage.

exposure present in some confined environments cause a progressive decrease of both densities and diversities. They are abundant in partially confined areas (mainly *Cyprideis torosa*) and the low polluted, intermediate deeper areas of the lagoon, whereas the specimens belonging to opportunistic species of Loxoconchidae are dominant in the low oxygenated zones close to the treatment station of Nador.

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