Seasonal variations of phytoplankton community in relation to environmental factors in a protected meso-oligotrophic southern Mediterranean marine ecosystem (Mellah lagoon, Algeria) with an emphasis of HAB species

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Abstract The spatial and temporal variation of phytoplankton communities including HAB species in relation to the environmental characteristics was investigated in the protected meso-oligotrophic Mellah lagoon located in the South Western Mediterranean. During 2016, a biweekly monitoring of phytoplankton assemblages and the main abiotic factors were realized at three representative stations. Taxonomic composition, abundance, and diversity index were determined. In total, 227 phytoplankton species (160 diatoms and 53 dinoflagellates) were inventoried. There was a clear dominance of diatoms (62.9%) compared with dinoflagellates (36.8%). Diatoms dominated in spring and

dinoflagellates developed in summer and early autumn in Mellah showing a marked seasonal trend. Data showed that the dynamic of the phytoplankton taxa evolving in the lagoon was mainly driven by temperature and salinity. For the first time, a number of potentially toxic species have been identified, including 2 diatoms (*Pseudo-nitzschia* group *delicatissima*, *Pseudo-nitzschia* group *seriata*) and 5 dinoflagellates (*Alexandrium minutum*, *Alexandrium tamarense/ catenella*, *Dinophysis acuminata*, *Dinophysis sacculus*, *Prorocentrum lima*). These harmful species could threat the functioning of the Mellah lagoon and human health and require the establishment of a monitoring network. Finally, our study suggests that the observed decrease of the phytoplankton diversity between 2001 and 2016 could result from the reduction in water exchanges between the lagoon and the adjacent coast following the gradual clogging of the channel.

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Introduction

Due to the wide variability of their physical, chemical, and biological parameters, coastal lagoons are generally unstable environments. The short- or long-term variations that occur in these ecosystems are important

compared with coastal marine environments. Consequently, the spatial and temporal variability of the characteristics of their waters depends on the importance of freshwater inputs, seawater renewal driven by tidal flows, and evaporation. The lagoon generally has estuarine features with high primary production and serves as a transition zone between the land and the sea (Natij et al. 2014). In many cases, coastal lagoons are eutrophic environments receiving high nutrient inputs from anthropogenic and indigenous sources showing a high level of primary production (Nuccio et al. 2003). This is particularly true for a large number of Mediterranean lagoons because of their shallow waters and low volumes, making them more vulnerable to global change than other aquatic systems (Le Fur et al. 2018).

Phytoplankton forms the basis of the food webs of aquatic ecosystems, represents an important biological component (Sin et al. 1999), and influences greatly the nutrient cycling. Phytoplankton was extensively studied in northern western Mediterranean lagoons (Nuccio et al. 2003; Bernardi Aubry and Acri 2004; Turki et al. 2007; Daoudi et al. 2012; Pulina et al. 2012). Unfortunately, phytoplankton studies in southern Mediterranean lagoons in general and in Algeria in particular remain scarce. Indeed, phytoplankton of the Mellah lagoon, located in southern Mediterranean Sea, has been studied only in two occasions. The first study was punctual (October 1989) in the context of the classification of the Mellah lagoon in the containment scale proposed by Guelorget et al. (1989). The second work is a doctorate thesis work on the structure and functioning of the lagoon (Draredja 2007), whose results concerning the distribution of phytoplankton have never been published. Thus, information is still lacking on phytoplankton which is a key factor in the functioning of the Mellah lagoon ecosystem. Hence, Mellah lagoon evolved in a protected national park, far from any source of pollution. It could be considered as a reference of south Mediterranean lagoons. The present work was devoted to highlight the spatio-temporal distribution and composition of phytoplankton assemblages of phytoplankton in the Mellah lagoon which would help us to better understand its ecological functioning. We aimed to study during 1 year and in three representative stations, the taxonomic composition and abundance of phytoplankton populations, their diversity, biomass, and species richness. Moreover, the relationships between phytoplankton dynamic and the main environmental parameters (temperature, salinity, nutrients) were investigated to highlight the driving factors. Until now, nothing is known on potentially toxic species in this ecosystem. The present study aimed also to identify for the first time Harmful Algal Blooms species (HABs) developing in this lagoon which could represent in the near future a threat to aquaculture and fisheries activities and impact the human health. The narrow and shallow channel connecting Mellah lagoon to the Mediterranean Sea has not been dredged since 1988 and was filled gradually with a significant decrease in water exchanges. Here, we compared the diversity and dynamics of phytoplankton following the disruption of the hydrodynamics of this lagoon.

Materials and methods

Study site and location of stations

Located in a natural site belonging to the El-Kala National Park, Mellah is the only lagoon in Algeria. The poorly urbanized area is occupied by a very sparse population in dwellings identified by the presence of houses mostly of traditional type. As a result, freshwater inputs include only soil leaching products. It is located in the northeast of Algeria (36.54° N and 08.20° E) and communicates with the sea by a long (900 m) and narrow (10–20 m) channel with a maximum depth of 2.5 m (Fig. 1). The lagoon totals an area of 865 ha, with a maximum depth of 5 m. Freshwater inputs are provided by three seasonal rivers and rainfall. The samples were collected biweekly during 2016, at three representative stations (Fig. 1): Station 1 (St.1) in the north near the channel separating Mellah to the Mediterranean Sea (2.5 m depth), Station 2 (St.2) located in the center of the lagoon which is the deepest zone (4.5 m depth), and Station 3 (St.3) in the southern part of Mellah far from marine influence (1.5 m depth).

Physical and chemical parameters

Physical parameters measurements and analyzes of water were performed in the sub-surface (about − 50 cm). Water temperature, salinity, pH, and dissolved oxygen were measured in situ using a multiparameter probe "HANNA HI9828." For chemical variables analyses, water samples were collected in 1000-mL polypropylene bottles. In the laboratory, water samples were filtered through a 47-mm/1.2-μm Whatman GF/C filter for dissolved inorganic nitrogen (NO_3, NO_2, NH_4), phosphates (PO_4), and chlorophyll a (Chl-a). Nutrient
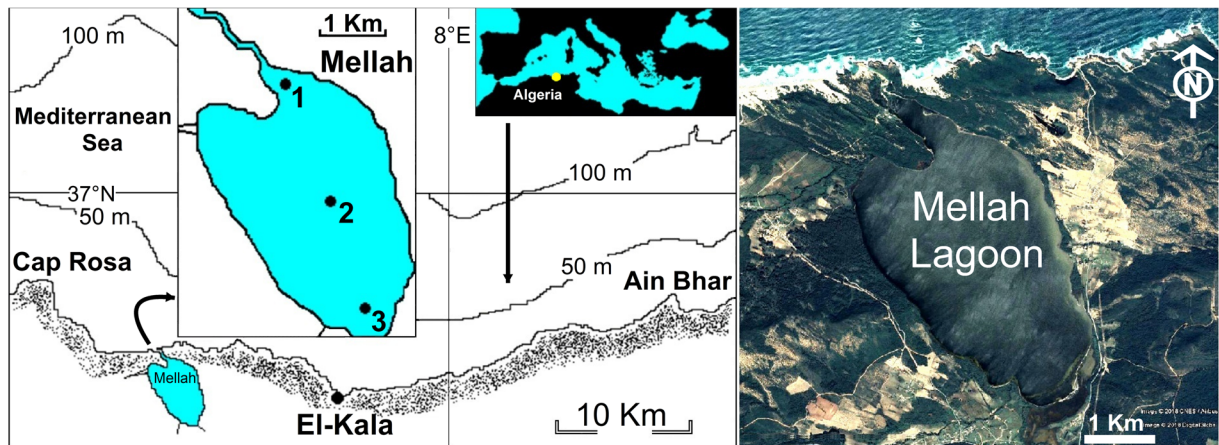
Fig. 1 The study area and location of sampling stations in the Mellah lagoon (southern Mediterranean Sea)

concentrations were determined by spectrophotometric analyses (Aminot and Chaussepied 1983). Chlorophyll *a* was extracted in darkness for 24 h at 4 °C using a 90% acetone solution after filtering the lagoon water and determined by spectrophotometric analysis (Lorenzen 1967). Determination of the suspended matter was performed according to Aminot and Chaussepied (1983).

Sampling and treatment of phytoplankton

Biweekly sampling of phytoplankton was conducted in surface waters in parallel with physical and chemical measurements, where a volume of 50 L of water was filtered through a plankton net (20 μm mesh size). The identification of different phytoplankton groups was performed according to Dodge (1982), Sournia (1984, 1986), Ricard (1987), Bourrelly (1988), Chrétiennot-Dinet et al. (1993), and Tomas (1997). The abundance of phytoplankton was estimated using Utermöhl's method (Utermöhl 1958). Both the identification and counting of phytoplankton (cells L^{-1}) were performed by an inverted light microscope (Leica DM750) with a Sony XCD-U100CR digital camera, using phase contrast optics 40X objective.

Ecological indices and statistics

The spatial and temporal variation of phytoplankton species richness (S) was calculated. The diversity index (H′) used is that of Shannon and Weaver (1949). The evenness index (J′) was calculated using the method of Piélou (1966). Ecological indices were performed using PAST3 software (Palaeontological Statistics, ver. 1.19)

(Hammer et al. 2001). Data from environmental parameters were tested using the two-way analysis of variance (ANOVA); they were performed using MINITAB Software (Version 16.1, PA State College, USA). A principal component analysis (PCA) was performed on standardized data, whose objective is to characterize by a multivariate approach the structure of the main phytoplankton groups. In addition, a Spearman correlation was performed to better visualize the interactions between the different environmental factors and the main phytoplankton groups in three stations.

Results and discussion

Hydrological and environmental conditions

The spatial and temporal variations in temperature were between 12.2 °C which was the minimum value registered in St.1 at late January and the maximum value of 28.8 °C registered at St.2, early July (Fig. 2A). Salinity in the Mellah lagoon showed a minimal value of 23.9 in St.3 at the end of February and a maximum of 36.2 in St.1 at the end of September (Fig. 2B). The highest levels of dissolved oxygen were recorded in the cold period with values of up to 8.7 mg L^{-1} (St.1, early January), as well as during phytoplankton blooms in early summer of up to 8.5 mg L^{-1} (St.3, end of June) and autumn with 8.7 mg L^{-1} (St.1, early October) (Fig. 2C). During the warm season, the lagoon waters were depleted in dissolved oxygen which dropped to 5.2 mg L^{-1} (St.3, early August). pH of the lagoon waters was slightly alkaline with values ranging from 7.7 (St.1, early May) to 8.5 (St.2, end of June) (Fig.

2D). The highest concentrations of suspended matter were recorded during the river flow in winter season with up to 38.5 mg L^{-1} (St.3, early January). The rest of the year the concentrations were low with 3.7 mg L^{-1} (St.3, end of September). The highest concentrations of dissolved inorganic nitrogen (DIN) were recorded during the winter, with a maximum of 8 µmol L^{-1} in St.2 at the end of January and in the autumnal season in St.1 at early October. The lowest concentration of 0.3 µmol L^{-1} was recorded at the beginning of winter in St.3 at the end of December (Fig. 3A). Nitrite, nitrate, and ammonium concentrations followed this tendency (Fig. 3B, C, D). The phosphorus (PO_4) values were varied between 0.02 in all the stations at the end of November and 1.7 µmol L^{-1} in St.3 at the end of January. The highest values of this nutrient have been recorded during the wet season (Fig. 3E). The mean values of physicochemical characteristics and chlorophyll a are reported in Table 1. Overall, the two-way ANOVA revealed non-significant effects of sites ($p > 0.05$), highly significant time differences ($p < 0.001$), and interactions ($p < 0.05$) for all environmental parameters measured.

We observed significant fluctuations in temperature and salinity in Mellah lagoon in function of the seasons. This was shown in other Mediterranean lagoons and ponds, among them Venice (Solidoro et al. 2004), Orbetello (Lenzi et al. 2003), Di Lagoon, Sacca Goro (Mistri et al. 2001), and Thau (Plus et al. 2003). Mellah seems to be sensitive to changes in air temperature because of its shallow water column (< 5 m). Salinity variation in the Mellah was positively correlated to changes in temperature. Salinity is also influenced by water exchange with the Mediterranean Sea throughout an arrow channel located in the north of Mellah. Even if dredging of this channel every 10 years was recommended (FAO 1987) to improve the hydrodynamic in this ecosystem, this was not done and the last and only dredging have been performed in 1988. Since then, this channel has known a gradual filling inducing a decrease in water exchange between the lagoon and the coastal Mediterranean waters. The inflow of freshwater in Mellah lagoon is due to the rainfall and the rivers that discharge there in rainy season. Draredja (2007) reported a vertical homogeneity of the salinity which indicates a well-mixed water column. Our results showed that the waters of the Mellah are well oxygenated (around 7.1 mg L^{-1}). The lower oxygen concentrations values were recorded at St.3 (South) far enough from marine influence. In contrast, the northern part of the lagoon (St.1) located near the channel showed the most oxygenated waters with

mean annual values of 6.9 and 7.3 mg L^{-1}, respectively. This was probably due to the more important water renewal in St.1 due to water bodies entering from the Mediterranean through the channel at the favor of tidal currents. These results corroborated those of Ounissi et al. (2002). Interestingly, when compared with other Mediterranean lagoons, the Mellah showed less important seasonal variations in dissolved oxygen level (5.8 to 8.1 mg L^{-1}). As an example, Mistri et al. (2001) reported dissolved oxygen values up to 14.5 mg L^{-1} in the waters of the Sacca di Goro lagoon. In contrast to the majority of Mediterranean lagoons, Mellah appears to be the least enriched in nutrients (Viaroli et al. 1993; Bianchi et al. 2003; Lenzi et al. 2003; Bernardi Aubry and Acri 2004; Bianchi et al. 2004). Indeed, the different forms of nitrogen (DIN) are relatively low in the lagoon with concentrations varying between 0 and 8.5 µmol L^{-1}. Phosphorus (PO_4) concentrations ranged between 0.02 and 1.5 µmol L^{-1}. The lagoon waters become richer in phosphates during the phase of river inputs corresponding to the wet season, with the highest content of 1.7 µmol L^{-1} at the end of January 2016. Many Mediterranean lagoons know eutrophication (Sfriso 1995; Viaroli et al. 1993; Lundin and Linden 1993; De Casabianca et al. 1994), while the Mellah lagoon is distinguished by its meso-oligotrophy (OECD 1982). The low enrichment in nutrients of the waters of the Mellah lagoon results in a moderate Chlorophyll a concentrations (4.5 µg L^{-1}) (Magni et al. 2015) compared with other Mediterranean lagoons (Triantafyllou et al. 2000; Nuccio et al. 2003; Solidoro et al. 2004; Bernardi Aubry et al. 2013).

Biomass, composition, and distribution of phytoplankton communities

The highest chlorophyll a concentration was found in spring-summer transition with values up to 5.5 µg L^{-1} (St.1, early June) and 5.5 µg L^{-1} (St.1, late June and St.2, late August), and autumn 5.5 µg L^{-1} (St.1, early October) and 5.3 µg L^{-1} (St.3, early October), while the less value recorded is 0.08 µg L^{-1} (St.1, early November) (Fig. 4). During November, there was a remarkable difference of 4.6 µg L^{-1} between the North of the lagoon (St.1: 0.08 µg L^{-1}) and the South (St.3: 4.6 µg L^{-1}) (Fig. 4). The evolution of chlorophyll a showed significant spatio-temporal variations (ANOVA, $p < 0.001$). Chlorophyll biomass showed two peaks, the first one in late spring and early summer (5.4 ± 0.1 µg L^{-1}) and the second one was observed in autumn (5.3 ± 0.2 µg L^{-1}). Our results corroborated those of
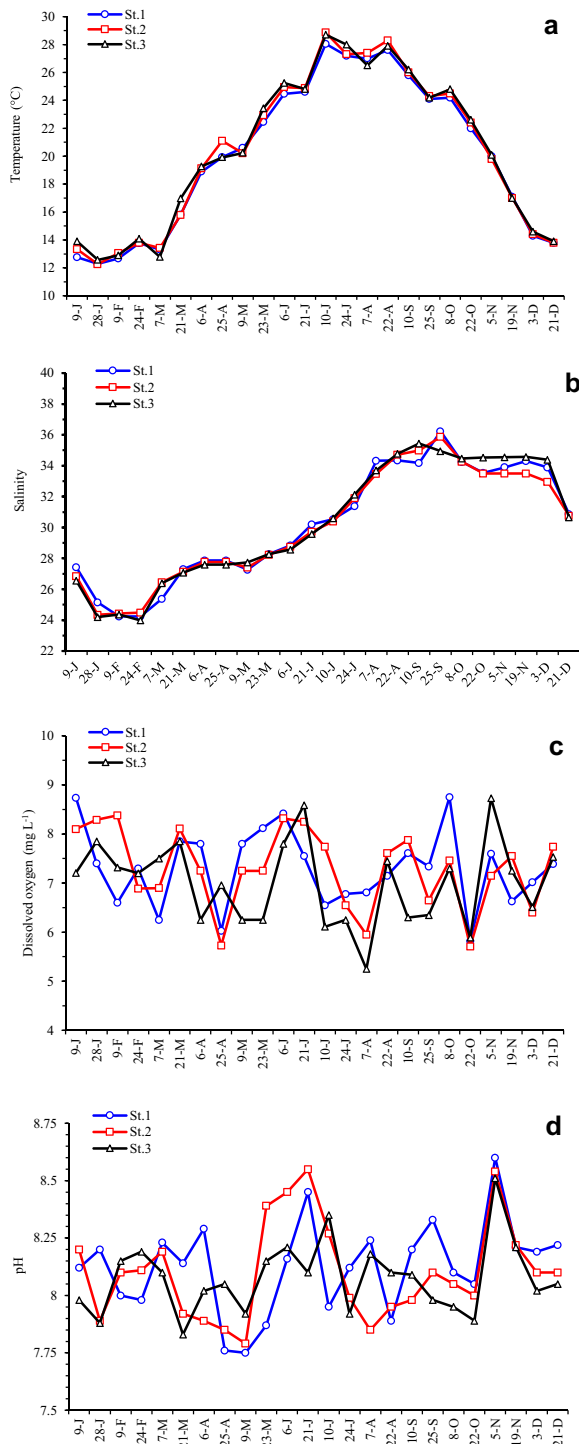
Fig. 2 Spatial and temporal variations of **a** temperature (°C), **b** salinity, **c** dissolved oxygen (mg L^{-1}), and **d** pH in the Mellah lagoon waters during 2016
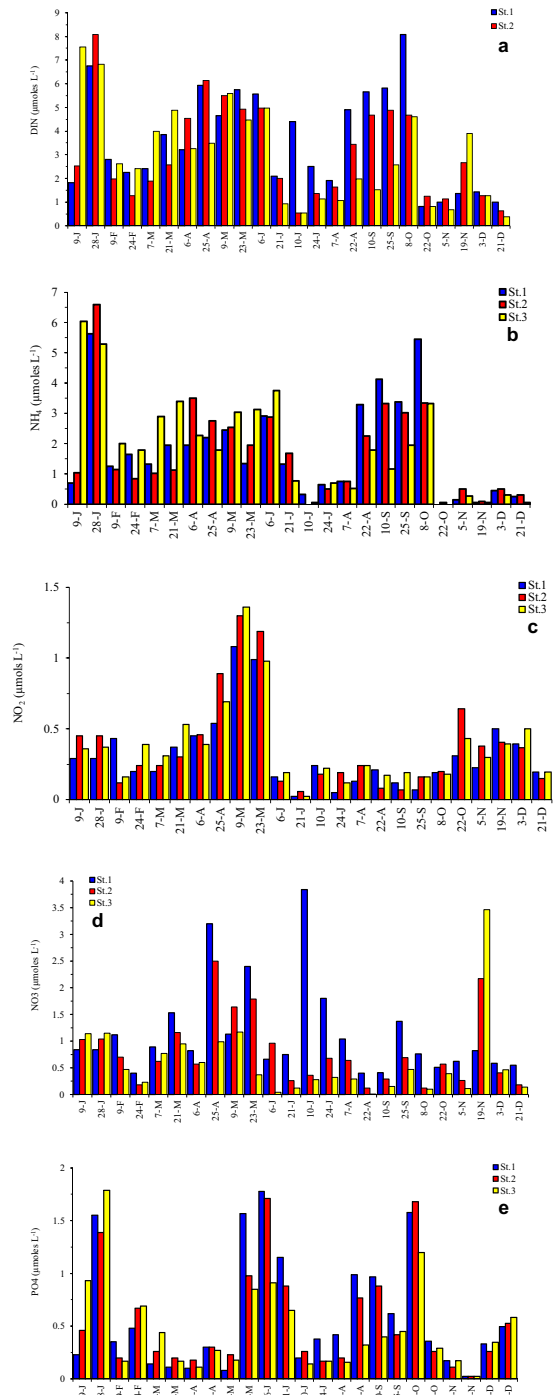
Fig. 3 Spatial and temporal variations of **a** dissolved inorganic nitrogen (DIN in μmol L^{-1}), **b** ammonium (NH$_4$ in μmol L^{-1}), **c** nitrite (NO$_2$ in μmol L^{-1}), **d** nitrate (NO$_3$ in μmol L^{-1}), and **e** phosphorus (PO$_4$ in μmol L^{-1}) in the Mellah lagoon waters during 2016

Table 1 The minimum and maximum of average values of physical and chemical parameters measured in the three sampled stations (St.1, St.2, and St.3) in the Mellah lagoon during 2016

Parameters	Mean ± sd	
	Minimum	Maximum
Temperature (°C)	12.3 ± 0.1 (end of January)	28.5 ± 0.4 (earlyof July)
Salinity	24.2 ± 0.2 (end of February)	35.6 ± 0.6 (end of September)
Dissolved oxygen (mgL^{-1})	5.8 ± 0.2 (end of October)	8.1 ± 0.5 (end of June)
pH	7.8 ± 0.08 (early May)	8.5 ± 0.04 (early November)
Suspended matter (mgL^{-1})	5.1 ± 1.4 (end of September)	34.3 ± 3.7 (early January)
Ammonium (NH$_4$) (µmol·L^{-1})	0.01 ± 0.02 (end of October)	5.8 ± 0.6 (end of January)
Nitrites (NO$_2$) (µmol·L^{-1})	0.03 ± 0.02 (end of June)	1.2 ± 0.1 (early May)
Nitrates (NO$_3$) (µmol·L^{-1})	0.1 ± 0.2 (end of August)	2.2 ± 1.1 (end of April)
DIN(*) (µmol·L^{-1})	0.6 ± 0.3 (end of December)	7.2 ± 0.7 (end of January)
Phosphate (P0$_4$) (µmol·L^{-1})	0.02 ± 0.0 (end of November)	1.5 ± 0.2 (end of January)
Chlorophyll a (µg L^{-1})	0.7 ± 0.3 (early December)	5.4 ± 0.1 (early June)

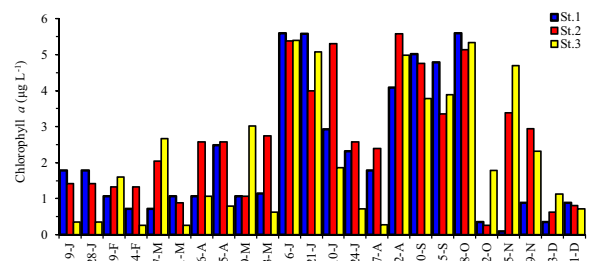$^{(*)}$ Dissolved inorganic nitrogen (NH$_4$ + NO$_2$ + NO$_3$)

Draredja (2007) who performed a field survey of Mellah lagoon in 2001. The average chlorophyll a concentration in the Mellah remains relatively low (around 2.4 µg L^{-1}). Mihnea (1992) reported an annual average Chl-a of 5 µg L^{-1} for eutrophic zones, whereas Bricker et al. (1999) describe as low eutrophised environments those characterized by a maximum Chl-$a \le 5$ µg L^{-1}. The Mellah lagoon is below these limits, so it could be classified among meso-oligotrophic sites in the Mediterranean basin. The main physicochemical parameters studied in the Mellah lagoon pointed to the relatively good condition of the lagoon since no excessively high values were found for nutrients or chlorophyll, indicating the meso-oligotrophy of the waters as observed in previous studies (Draredja 2007; Magni et al. 2015). This fact contrasts with other Mediterranean coastal lagoons, in which eutrophication processes have been reported and which maintain high nutrient and phytoplankton concentrations (Table 2).

Phytoplankton of Mellah Lagoon was characterized by a mixture of marine, brackish-water, and freshwater taxa, mainly represented by two groups: diatoms and dinoflagellates. In all of the stations, 227 species of phytoplankton were identified (Appendix 1). Diatoms were the dominant group and were represented by 160 species. The dinoflagellates were represented by 53 species. The other groups were much less rich in species: 7 Cyanophyceae, 3 Chlorophyceae, 2 Conjugatophyceae, 1 Dictyophyceae, and 1 Euglenophyceae (Appendix 1). The diatoms were represented by 52 centric and 108 pennate species. Among the Centrales, 15 families such as Catenulaceae (15

species), Thalassiosiraceae (8 species), and Triceratiaceae (5 species), while the Pennales contain 23 families, which 3 are the most rich in species: Bacillariaceae (22 species), Naviculaceae (16 species), and Pleurosigmataceae (14 species) (Appendix 1). Diatoms formed the most dominant taxa and contributed greatly to the total population at almost all the stations. They were represented over 62.9% of total species compared with 36.8% of the dinoflagellates. The other groups represented only 0.1%. The contribution of the different phytoplankton groups in the three stations is quite similar during the study period, with diatoms dominance (55.7–70.3%).

The temporal variations of the contribution of the different groups show a clear dominance (> 90%) of diatoms at the end of spring season (Fig. 5). The spatio-temporal survey during 2016 of phytoplankton species in the Mellah lagoon allowed us to identify 227 taxa, most of them (68.2%) are marine. Three diatoms (*Achnantes bervipes*,

Fig. 4 Spatial and temporal variations of chlorophyll a (µg L^{-1}) in the Mellah Lagoon waters during 2016

Table 2 Main physical and chemical parameters of some Mediterranean lagoons. T, temperature (°C); Sal, salinity; DIN, dissolved inorganic nitrogen (µmol L^{-1}); SRP, soluble reactive phosphorus (µmol L^{-1}); and Chl-a, chlorophyll a (µg L^{-1}). (A, Algeria; F, French; G, Greece; I, Italy; S, Spain; and T, Tunisia)

| Lagoon	T	Sal.	DIN	SRP	Chl-a	References
Biguglia (F)	9–27.5	4–26	0.7–77.1	–	–	Pasqualini et al. (2006)
Urbino (F)	6–31	26–44	0.2–5.5	–	–	Pasqualini et al. (2006)
Thau (F)	4–27	29–42	20.7–136.1	0.1–20.9	1.1–14.1	Vincent et al. (2006)
Gialova (G)	10.7–29.7	26–44	0.08–44.5	0.01–0.2	0.08–11.7	Petihakis et al. (1999)
Logarou (G)	13–24	15.7–26.6	0–8.7	0.12–1	1.8–20.9	Kormas et al. (2001)
Tsoukalio–Rodia (G)	11.3–28.3	11.6–28.9	0–9.3	0–0.1	0.2–6.5	Kormas et al. (2001)
Orbetello (I)	6–28	–	12–85.1	0.1–0.9	–	Lenzi et al. (2003)
Venice (I)	4.8–32	25–33	2–41.5	0.3–2.9	0.2–29.1	Sfriso (1995)
Cabras (I)	6.6–29.3	2–41	286–16	0.2–4	4–197	Pulina et al. (2012)
Mar Menor (S)	10.2–30.7	41.5–46.1	1.5–8.9	0–0.6	0.7–5.6	Lloret et al. (2008)
Ghar El Melh (T)	11–26.9	35.5–51	2.9–7	0.06–0.3	–	Dhib et al. (2016)
Mellah (A)	12.2–28.8	23.4–36.2	0.3–8	0.02–1.7	0.08–5.5	Present study

Paralia sulcata, *Pleurosigma formosum*) and one dinoflagellate (*Prorocentrum micans*) were the most constantly present in Mellah. In terms of species diversity, Bonin (1988) suggested that diatom richness is related not only to turbulent tidal regime leading to release of benthic and tychopelagic forms in the water column but also to the ability of diatom species to directly draw nutrients from the water-sediment interface. Draredja (2007) recorded 359 phytoplankton species during an annual survey performed in 2001 with diatoms dominance (94–98%). After a period of 15 years, we interestingly noted the lack of 132 phytoplankton species. This could be explained by the gradual clogging of the channel decreasing in turn the entrance of coastal marine water and in turn the phytoplankton species from the adjacent Mediterranean area. Despite this situation, it is interesting to note that, unlike polluted coastal environments where Dinophyceae dominate (Béthoux et al. 2002), the Mellah is rather dominated qualitatively and quantitatively by Diatomophyceae. This difference reflects the good quality of the Mellah waters and a better distribution of the population. Our results showed sporadic development of some taxa characterizing eutrophic environments (Lakkis and Zeidane 1985), among them *Licmophora abreviata*, *Striatella unipunctata*, *Thalassionema nitzschoides*, *Coscinodiscus* sp., *Tripos furca*, and *Prorocentrum micans*. In Mellah, we found about 155 species with marine affinity, whereas species showing freshwater affinity accounted for 40 species and were found mainly in St.2 and St.3 far from marine influences. Our results showed that few species were responsible of the major proliferations among them 3 diatoms (*Chaetoceros constrictus*, *Chaetoceros* sp. and *Nitzschia longissima*) and 2 dinoflagellates (*Scrippsiella trochoidea* and *Diplopsalis lenticula*). For the first time, a number of potentially toxic species have been identified, including 2 diatoms (*Pseudo-nitzschia* group *delicatissima*, *Pseudo-nitzschia* group *seriata*) and 5 dinoflagellates (*Alexandrium minutum*, *Alexandrium catenella/tamarense*, *Dinophysis acuminata*, *Dinophysis sacculus*, *Prorocentrum lima*). Not far from the Mellah (150–200 km at the East), the Tunisian Mediterranean lagoons have experienced significant proliferation of toxic phytoplankton species. For example, it has been shown that in Bizerte lagoon the neurotoxic dinoflagellate *Alexandrium catenella* caused in 2007 an important bloom with concentrations up to 2.6×10^6 cells L^{-1} and intoxications of oysters with paralytic toxins (Turki et al. 2007; Fertouna-Bellakhal et al. 2015). Even the abundances of the HABs species were relatively low in Mellah lagoon, they could potentially form blooms in the coming decades at the favor of warming affecting and trophic status changes in Mediterranean marine systems. Hence, aquaculture activity (mussels and fish farming) is developing in Mellah lagoon; this could result of potential intoxication of seafood with a threat for human health. Consequently, monitoring program must be established to gain more insight in the development of potentially toxic species and the toxins produced.

Population density and distribution

The average abundance of phytoplankton was higher at station 1 (223,990 cells L^{-1}, early September) and 2 (298,415 cells L^{-1}, early October) near of marine inputs, compared with station 3 (173,130 cells L^{-1}, early June) located in the south of the lagoon. The spatio-temporal variation in the density of the different phytoplankton groups is shown in Fig. 6. In the surveyed three stations, diatoms were generally the most abundant throughout the study period. According to the period and the station, among the 227 species distributed; only a few (about 10) are dominant. The majority of the species are therefore very poorly represented. During this study, a few species causing blooms were detected. Among the diatoms, we report 3 species that were highly represented including *Chaetoceros* sp. with up to 178,320 cells L^{-1} (St.2, early October), *Chaetoceros constrictus* with up to 15,000 cells L^{-1} (St.2, end of May) and *Nitzschia longissima* with up to 200,640 cells L^{-1} (St.1, early September). The dinoflagellate *Scrippsiella trochoidea* was responsible of the observed blooms with up to 107,250 cells L^{-1} (St.1, end of August), *Diplopsalis lenticula* up to 10,250 cells L^{-1} (St.1, end of October). Moreover, the inventory of the phytoplankton of the Mellah lagoon contains seven potentially HAB species: 2 diatoms: *Pseudo-nitzschia* group *delicatissima* (2520 cells L^{-1}), *Pseudo-nitzschia* group *seriata* (700 cells L^{-1} and 5 dinoflagellates: *Alexandrium minutum* (1420 cells L^{-1}), *Alexandrium catenella/ tamarense* (1350 cells L^{-1}), *Dinophysis acuminata* (180 cells L^{-1}), *Dinophysis sacculus* (120 cells L^{-1}), and *Prorocentrum lima* (110 cells L^{-1}). The most represented HABs are shown in Fig. 7. The frequency of occurrence of these HAB species varies between 20.1 and 25% (Fig. 8), with a maximum in the center of the lagoon, the deepest zone characterized by a muddy bottom rich in dinocysts of the HAB species (Draredja et al. paper under review). In the whole lagoon the total abundance of the phytoplankton varies between 96,586 (end of May) and 166,841 cells L^{-1} (early June) at the end of spring and between 110,051 (early September) and 132,461 cells L^{-1} (early October) during summer-autumn transition. The first significant phytoplankton development coincided with the exogenous inputs of nutrients during the flood period in winter-spring and warming. The second bloom observed in summer-autumn transition period could result in an endogenous supply of nutrients following bacterial activity decomposing organic matter accumulated at the bottom of the lagoon. Generally, the two-way ANOVA for
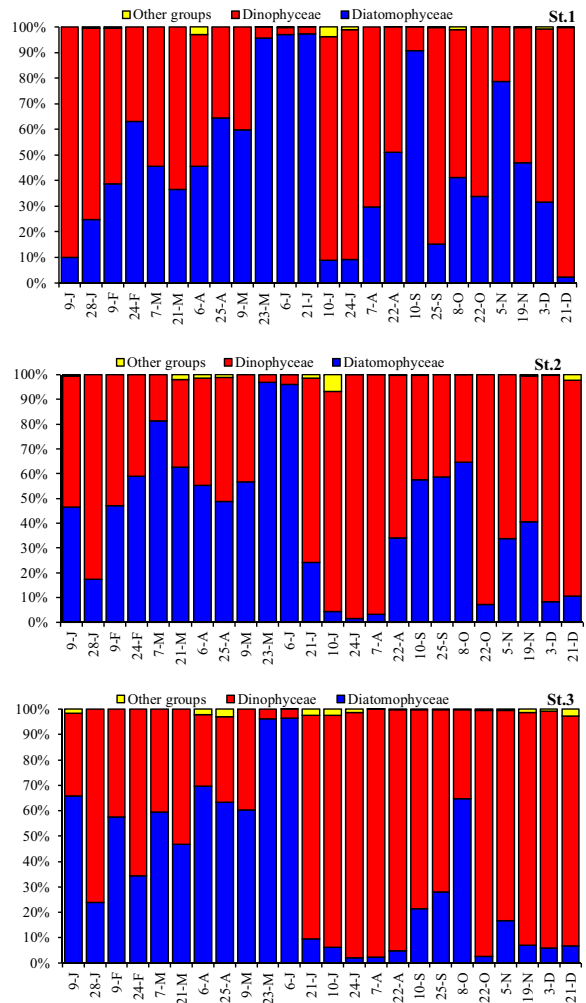
Fig. 5 Spatial and temporal variations of relative abundances (%) of different phytoplanktonic groups sampled in the Mellah lagoon waters during 2016

abundance distribution in the Mellah lagoon revealed a highly significant time difference ($p < 0.001$) for the total abundance of the phytoplankton.

Species diversity

The number of species (S) and range of diversity indices in the study area are shown in Fig. 9. The maximum number (48) of species was observed in the north of the Mellah at St.1 (early June). St.3 located in the south of the Mellah which was the least rich one with 43 species observed in early June (Fig. 9). St.2 in the center of the lagoon was characterized by a comparable number with 45 species. Shannon index of diversity (H′) values generally increased in parallel to the number of species (S)

and evenness (J′) throughout the study period. This trend was observed only for stable ecosystems. The highest diversity H′ = 3 bits cell^{-1} was observed at station 3 (end of April) and the lowest value H′ = 0.4 bit cell^{-1} was detected at the same station (early August) (Fig. 9). Evenness index (J′) varies between 0.1 (St.3, early August) and 0.9 (St.2, early August) (Fig. 9). On a seasonal basis, in general H′ decreased slightly from St.1 to St.3, despite the highest value of H′ was reported in this station. The northern zone (St.1) is under the direct influence of marine inputs with the entrance of marine Mediterranean waters with accompanying phytoplankton species present in the incoming water bodies. The phytoplankton in Mellah lagoon showed a diversity reaching 3 bits cell^{-1} and a regularity of 0.9, explaining a structured community from January to April. In the rest of the year, opportunistic species developed as they are well adapted to the adverse factors prevailing in situ.
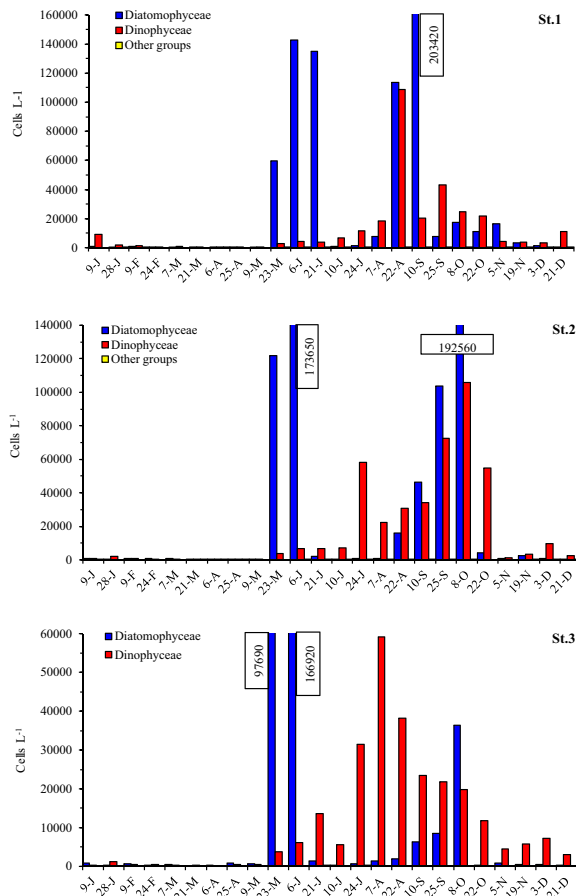

Fig. 6 Spatial and temporal variations of density (cells L^{-1}) of different phytoplanktonic groups sampled in the Mellah lagoon waters during 2016
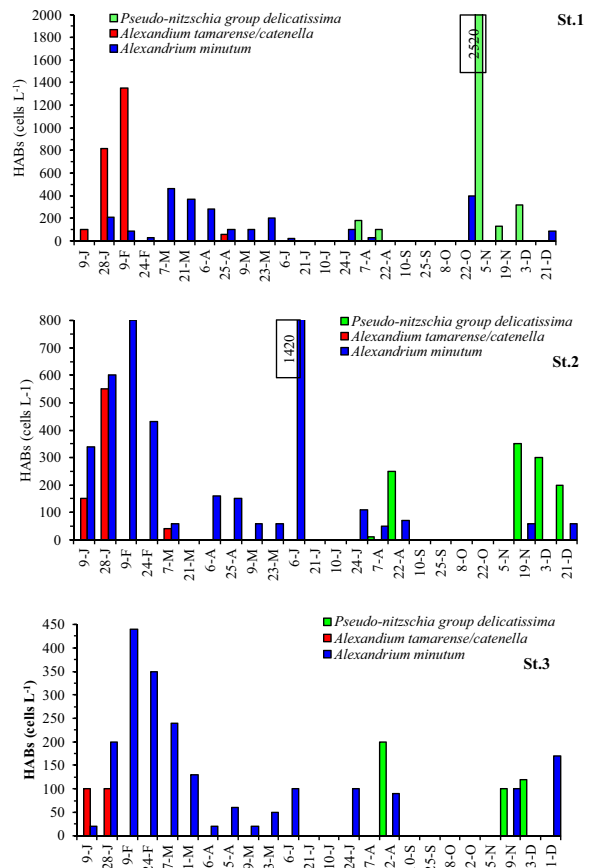
Fig. 7 Abundance of the main potentially harmful species (HABs) in the Mellah lagoon waters during 2016

Phytoplankton and environmental parameters correlation
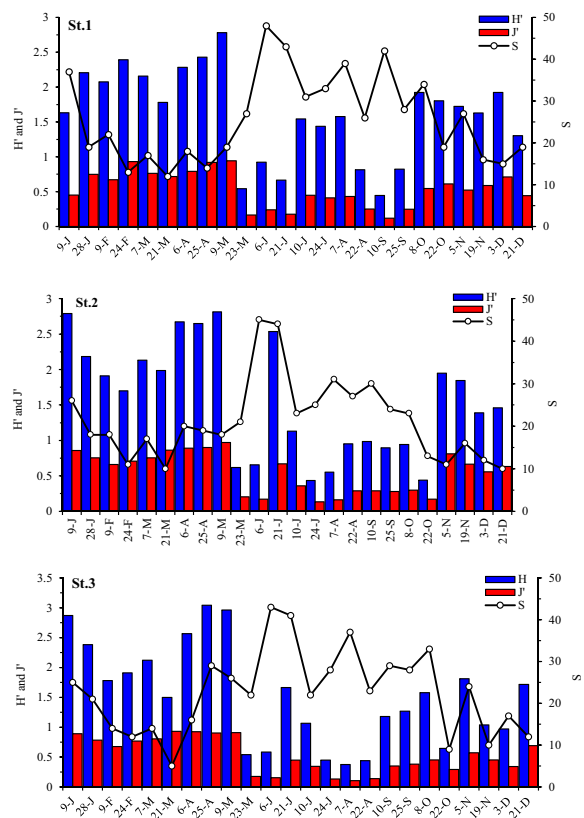
Spearman analyses indicate that the abundance of the microphytoplankton in the Mellah lagoon was related significantly to temperature ($r = 0.53$ and 0.58 for diatoms St.1 and St.3 respectively and for dinoflagellates $r = 0.55$; 0.65 and 0.77 St.1, St.2 and St.3 respectively) and salinity ($r = 0.61$; 0.51 and 0.42 for diatoms St.1, St.2, and St.3 respectively and for dinoflagellates $r = 0.80$; 0.78 and 0.83 St.1, St.2 and St.3 respectively) (Appendix 2). These factors were more correlated to dinoflagellates than diatoms. Phytoplankton abundance was significantly but poorly related to ammonia. Phosphorus (PO$_4$) was relatively well correlated with diatoms and dinoflagellates at St.1 and St.2. Chlorophyll a was positively correlated with diatoms ($r = 0.45$; 0.461 and 0.57 for St.1, St.2 and St.3 respectively and $p < 0.05$ for St.1 and St.2 and $p < 0.01$ for St.3). We observed that NO$_2$ were negatively correlated
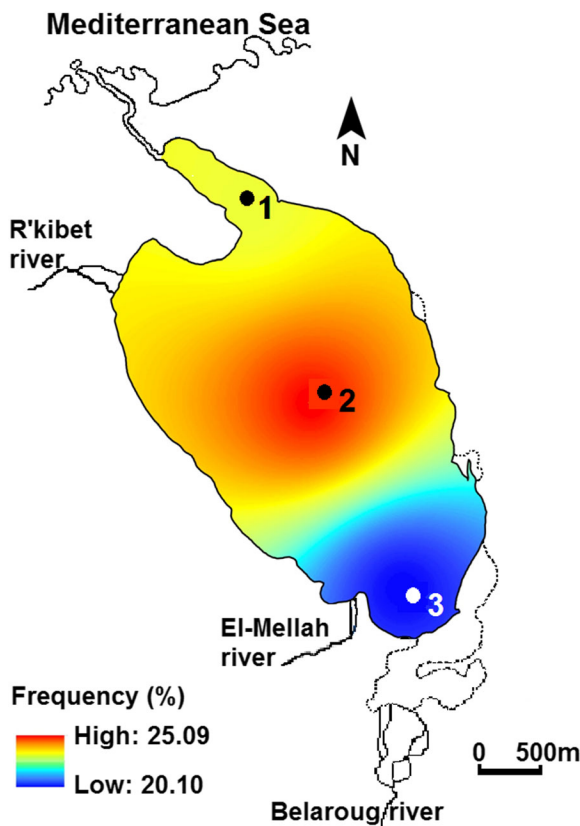
Fig. 8. The frequency of HABs in the Mellah lagoon. The frequency of HABs in the study area was mapped according to the appearance of these toxic species during 2016 with a sampling every 15 days.

Fig. 9 Spatial and temporal variations of species number (S), Shannon diversity index (H′), and Piélou evenness index (J′) of phytoplanktonin the Mellah lagoon waters during 2016

with diatoms and dinoflagellates at all stations. To a lesser extent, NO_3 were also negatively correlated to phytoplankton abundance except in St.3.

The use of principal component analysis (PCA) as a preliminary and exploratory descriptive approach made it possible to visualize the structuring of the Mellah main phytoplankton groups, according to 11 physico-chemical variables and the densities of diatoms and dinoflagellates groups in three stations (Fig. 10). Our results showed significant negative correlation between nitrites, nitrates, and the two dominating phytoplankton groups (diatoms and dinoflagellates) suggesting a significant uptake of these nitrogen resources for their development. In spite of the meso-oligotrophic fate of the Mellah lagoon, its specific richness is comparable or higher than some hyper and eutrophe Mediterranean lagoons (Nuccio et al. 2003; Fanuko and Valčić 2009; Daoudi et al. 2012; Pulina et al. 2012; El-Kassas and

Gharib 2016). This study clearly showed a seasonal trend in phytoplankton succession in Mellah lagoon. Diatoms dominated in spring, while dinoflagellates showed the higher densities in summer and early autumn. Multivariate analyses (PCA) showed that the dominating groups (diatoms and dinoflagellates) are significantly correlated to temperature and salinity. During winter, phytoplankton is poorly abundant because of the unfavorable environmental conditions, mainly low temperature and salinity. Draredja (2007) suggesting that the high turbidity within the water column prevailing in winter could also partly explain such low phytoplankton development. Our results showed a high suspended matter level in winter 2016 (data not shown). Together with a significant seasonal trend in the variation of phytoplankton species composition in the whole lagoon, our results also showed differences within the three sampled stations. As an example, St.3 was

Fig. 10 Principal component analysis for dominating phytoplankton groups (diatoms and dinoflagellates) in water column related to the environmental factors (temperature, salinity, PO_4 phosphorus, NO_2 nitrite, NO_3 nitrate, NH_4 ammonium) (axis 1–2). Red dots refer to active variables
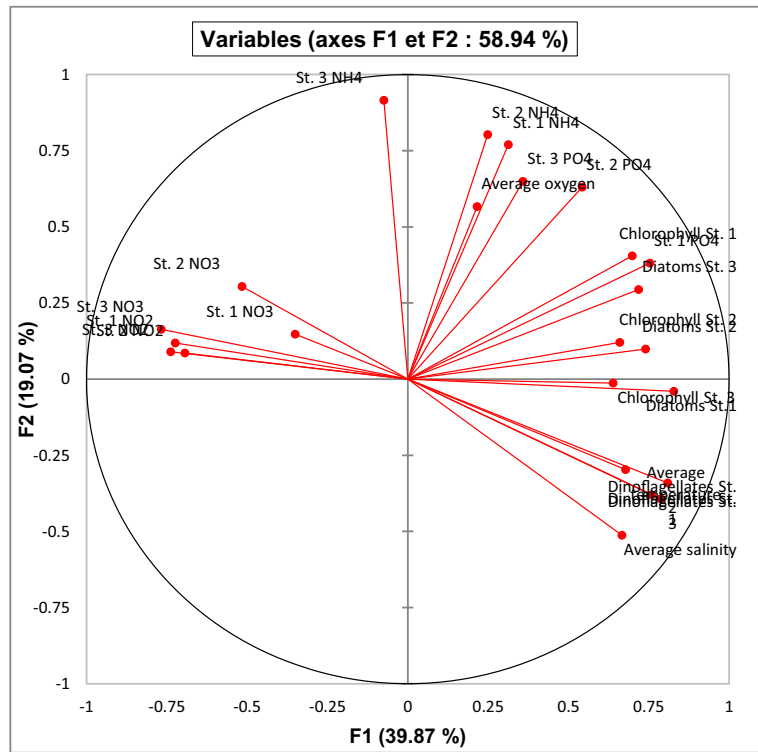
characterized by the dominance of dinoflagellates in summer and early autumn season.

Conclusion

Finally, our study suggests that, although the majority of Mediterranean lagoons are experiencing eutrophication problems, particularly in the summer season, Mellah lagoon remained meso-oligotrophe. This ecosystem belongs to the El-Kala National Park and shows an absence of significant agglomeration as well as anthropogenic activities resulting of an absence of nutrient and organic/metallic pollution. Interestingly, specific phytoplankton richness (227 species) is comparable or higher than those of some hyper and eutrophic Mediterranean lagoons. In general, the diatoms that dominated the phytoplankton community during most of the annual cycle show that the ecological quality of the Mellah lagoon as a whole is not degraded. However, a regular dredging of the channel must be established to improve the water exchange between the Mellah and Mediterranean Sea to stabilize the quality of lagoon waters and to increase phytoplankton species diversity as we demonstrated that this latter was negatively affected since the channel become more and more filled. The presence of some HAB species related to PSP (paralytic shellfish poisoning) as *Alexandrium catenella/tamarense*, *Alexandrium minutum*, DSP (diarrhetic shellfish poisoning) as *Dinophysis acuminata*, *Dinophysis sacculus*, *Prorocentrum lima*, ASP (amnesic shellfish poisoning) as *Pseudo-nitzschia* group *delicatissima* et *Pseudo-nitzschia* group *seriata*, need to implement a monitoring program to detect the proliferation of toxic species order to prevent any human intoxication due to the consumption of contaminated shells.

Appendix 1 Check list of phytoplankton species encountered in Mellah lagoon during 2016. (F: freshwater, M: marine, L: lagoon, T: potentially toxic). Classification depending on Website WoRMS: http://www.marinespecies.organd AlgaeBase: http://www.algaebase.org

CHLOROPHYCEAE (Wille Sensu Silva, 1982)

SPHAEROPLEALES

Hydrodictyaceae Dumortier, 1829
Pediastrum boryanum (Turpin) Meneghini, 1840 (F)

ScenedesmaceaeOltmanns, 1904
Scenedesmus oppliensis (P.G.Richter) E.Hegewald, 2000(F)

PRASIOLALES

Prasiolaceae Blackman & Tansley, 1902
Hormidinium sp. Kützing, 1843

CYANOPHYCEAE (Schaffner, 1909)

CHROOCOCCALES (Wettstein, 1924)

Chroococcaceae Rabenhorst, 1863
Chroococcus turgidus (Kützing) Nägeli, 1849 (F)

SYNECHOCOCCALES

Merismopediaceae Elenkin, 1933
Merismopedia punctata Meyen, 1839 (F)

NOSTOCALES (Atkinson, 1905)

Nostocacées Eichler, 1896
Anabaena macrospora Klebahn, 1895 (F)

OSCILLATORIALES

Oscillatoriaceae Engler, 1898
Lyngbya epiphytica var. *aquaedulcis* N.L.Gardner, 1927 (F)
Oscillatoria anguina Bory ex Gomont 1892 (F)
O. bonnemaisonii P.L.Crouan & H.M.Crouan ex Gomont, 1892 (M)
Oscillatoria sp.

DIATOMOPHYCEAE (Rabenhorst, 1864)

CENTRIC DIATOMS

Catenulaceae Mereschkowsky, 1902
Amphora arenaria Donkin, 1858 (M)
A. coffeaeformis (C.Agardh) Kützing, 1844 (M)
A. decussata Grunow, 1877 (M)
A. dubia Gregory, 1857 (M)
A. gigantea Grunow (M)
A. laevis Gregory, 1857 (M)
A. lineolata Ehrenberg, 1838 (M)
A. marina W.Smith, 1857 (M)
A. ocellata Donkin, 1861 (M)
A. ovalis (Kützing) Kützing, 1844 (M)
A. proboscidea Gregory, 1857 (M)
A. proteus Gregory, 1857 (M)
A. ostrearia Brébisson, 1849 (M)
A. sulcata Brébisson, 1854 (M)
A. terroris Ehrenberg, 1853 (M)

Chaetocerotaceae Ralfs, 1851
Chaetoceros constrictus Gran, 1897 (M)
C. pseudobrevis Pavillard, 1911 (M)
C. radicans F.Schütt, 1895 (M)
Chaetoceros sp.

Coscinodiscaceae Kützing, 1844
Coscinodiscus centralis Ehrenberg, 1844 (M)
C. obscurus Schmidt, 1858 (M)
C. subtilis Ehrenberg, 1841 (M)
Coscinodiscus sp.

Hyalodiscaceae Crawford, 1990
Hyalodiscus scoticus (Kützing) Grunow 1879 (M)
Podosira stelligera (Bailey) A.Mann, 1907 (M)

Hemidiscaceae Hendey, 1937 emend Simonsen, 1975
Pseudoguinardia recta Von Stosch, 1986 (F)

Lauderiaceae (Schütt) Lemmermann, 1899, sensu emend.
Lauderia borealis Gran, 1900 (M)

Leptocylindraceae Lebour, 1930
Leptocylindrus danicus Cleve,1889 (M)

LithosdemiaceaeRound, 1990
Lithodesmium undulatum Ehrenberg, 1839 (M)

Melosiraceae Kützing, 1844, sensu emend.
Melosira moniliformis (O.F.Müller) C.Agardh, 1824 (M)
M. nummuloides C.Agardh, 1824 (M)
Melosira sp.
Paraliaceae Crawford, 1988
Paralia sulcata (Ehrenberg) Cleve, 1873 (L)

Rhizosoleniaceae De Toni, 1890
Guinardia flaccida (Castracane) H.Peragallo, 1892 (M)
Rhizosolenia delicatula Cleve, 1900 (M)
*R. imbricata*Brightwell, 1858 (M)
*R. stolterfothii*H.Peragallo, 1888 (M)

Skeletonemaceae Lebour, 1930, sensu emend.
Skeletonema sp.

Syracosphaeraceae Lemmermann, 1908
Syracosphaera pulchra Lohmann, 1902 (M)

Thalassiosiraceae Lebour, 1930
Planktoniella sol (C.G.Wallich) Schütt, 1892 (M)
Thalassiosira fallax Meunier, 1910 (M, L, F)
T. lineata Jousé, 1968 (M)
T. nordenskioeldii Cleve, 1873 (M)
T. visurgis Hustedt, 1957 (L, F)

Triceratiaceae (Schütt) Lemmermann, 1899
Auliscus caelatus Bailey, 1854 (M)
Cerataulus radiatus R.Rross, 1986 (M)
Odontella cf. *rostrata* (Hustedt) Simonsen, 1987 (M, L)
Triceratium antediluvianum (Ehrenberg) Grunow, 1868
T. favus Ehrenberg, 1839 (M)
T. pelagicum (J.L.B.Schröder) Sournia, 1968 (M)
T. shadboltianum R.K.Greville, 1862 (M)
Triceratium sp.

PENNATE DIATOMS

Achnanthaceae Kützing, 1844
Achnanthes brevipes Agardh (L)

Amphipleuraceae Grunow, 1862
Amphiprora hyperborea (Grunow, 1880) (M)
Amphiprora sulcata (O'Meara, 1871) (M)
Amphiprora sp.

Auriculaceae Hendy, 1964
Auricula amphitritis Castracane, 1873 (M)

Bacillariaceae Ehrenberg, 1831
Bacillaria paxillifera(O.F.Müller) T.Marsson, 1901 (M)
Hantzschia virgata (Roper) Grunow in Cleve & Grunow 1880 (M)
Nitzschia acula (Kützing) Hantzsch *in* Rabenhorst, 1861 (F)
N. acuminata (W.Smith) Grunow, 1880 (M)
N. angularis Smith, 1853 (M)
N. closterium Eulenstein, 1868 (F)
N. constricta (Gregory) Grunow, 1880 (F)
N. cylindrus (Grunow ex Cleve) Hasle, 1972 (M)
N. dubia W.Smith, 1853 (F)
N. fasciculata (Grunow) Grunow in Van Heurck, 1881 (F)
N. incurva Grunow in O.Schneider, 1878 (F)
N. linearis W.Smith, 1853 (M, F)
N. longissima (Brébisson) Ralfs, 1861 (F)
N. obtusa W.Smith, 1853 (M, F)
N. polaris Grunow ex Cleve, 1883 (M)
N. punctata (W.Smith) Grunow, 1878 (M)
N. sigma (Kützing) W.Smith, 1853 (F)
N. spathulata W.Smith, 1853 (M)
N. ventricosa Kitton, 1873 (M)
Nitzschia sp.
Pseudo-nitzschia group *delicatissima* (Cleve) Heiden, 1928 (M) (T)
Pseudo-nitzschia group *seriata* (Cleve) H.Peragallo, 1899 (M) (T)

Climacospheniaceae
Climacosphenia monoligera Ehrenberg, 1843 (M)

Cocconeidaceae Kützing, 1844
Cocconeis molesta Kützing (M)
C. placentula Ehrenberg, 1838 (M)
C. pseudomarginata Gregory, 1857 (M)
C. stauroneiformis (W.Smith) H.Okuno, 1957 (M)
Cocconeis sp.

Cymatosiraceae Hasle, von Stosch & Syvertsen, 1983
Campylosira cymbelliformis (A.Schmidt) Grunow ex Van Heurck, 1885 (M)
Minutocellus scriptus Hasle, von Stosch & Syvertsen, 1983 (M)

Cymbellaceae (Greville, 1833)
Cymbella cymbiformis (Ehrenberg) Grunow in Van Heurck, 1880 (M)
Cymbella inaequalis Ross, 1852 (M)
Cymbella helvetica Schmidt in Schmidt *et al.*, 1881 (F)

Diploneidaceae D.G.Mann, 1990
Diploneis bomboides (A.W.F.Schmidt) Cleve, 1894 (M)
D. bombus (Ehrenberg) Ehrenberg, 1853 (M)
D. crabro (Ehrenberg) Ehrenberg, 1854 (L)
D. didyma (Ehrenberg) Ehrenberg, 1839 (M)
D. incurvata (Gregory) Cleve, 1894 (M)
Diploneis sp.

Fragilariacées (Dumortier, 1823)
Fragilaria islandica Grunow ex Van Heurck, 1881 (M)
Synedra acus Kützing, 1844 (F)
S. cristallina (L, F)
S. fasciculata Ehrenberg, 1832 (F)
S. ulna (Kützing) Skabichevskii, 1959 (F)
Synedra sp.

Licmophoraceae Kützing, 1844
Licmophora abbreviata C.Agardh, 1831 (M)
L. ehrenbergii (Kützing) Grunow, 1867 (M)
L. flabellata (Greville) Agardh (M)
L. reichardtii Grunow, 1881 (M)

L. robusta H.Peragallo & M.Peragallo (M)
L. tenuis (Kützing) Grunow, 1867 (M)
Licmophora cf. *tincta* (C.Agardh) Grunow, 1868 (M)

Lyrellaceae D.G.Mann
Lyrella hennedyi (W.Smith) Stickle & D.G.Mann, 1990

Naviculaceae (Kützing, 1844)
Haslea ostrearia (Gaillon) Simonsen, 1974 (M)
H. wawrikae (Hustedt) Simonsen, 1974 (M)
Navicula cryptocephala Kützing, 1844 (M)
N. distans (W.Smith) Ralfs, 1861 (M, L)
*N. flanatica*Grunow, 1860 (L, F)
N. gregaria Donkin, 1861 (M, L, F)
N. pavillardi Hustedt, 1939 (L)
N. pennata A.W.F.Schmidt (F)
N. pupula Bristol, 1920 (F)
N. radiosa Kützing, 1844 (F)
N. ramosissima (C.Agardh) Cleve, 1895 (M)
N. retusa H.Lange-Bertalot & K.Bonik, 1976 (M, L)
N. salinarum Grunow, 1880 (L, F)
N. spicula (Hickie) Cleve, 1894 (M, F)
N. viridula Neupauer, 1867 (F)
Navicula sp.

Pinnulariaceae D.G. Mann, 1990
Oestrupia sp.

Plagiotropidaceae D.G. Mann
Plagiotropis lepidoptera (Gregory) Kuntze, 1898 (L)
P. conserta (Lewis) Kuntze, 1898 (M)
P. vitrea (W.Smith) Grunow, 1880 (M)
Plagiotropis sp.

Pleurosigmataceae Mereschkowsky, 1903
Gyrosigma balticum (Ehrenberg) Rabenhorst, 1853 (M)
G. distortum (W.Smith) Griffith & Henfrey, 1856 (M, F)
G. littorale (W.Smith) Griffith & Henfrey, 1856 (M)
G. prolongatum (W.Smith) J.W.Griffith & Henfrey 1856 (M)
G. scalproides (Rabenhorst) Cleve, 1894 (L, F)
Pleurosigma angulatum (Queckett) W.Smith, 1852 (M)
P. delicatulum W.Smith, 1852 (M)
P. elongatum W.Smith, 1852 (M, L, F)
P. formosum W.Smith, 1852 (L)
P. giganteum Grunow, 1880
P. lanceolatum Donkin, 1858 (M)
P. obscurum W.Smith, 1852 (L)
P. stuxbergi Cleve & Grunow, 1880 (M)
Pleurosigma sp.

Rhabdonemataceae Round & R.M.Crawford
Rhabdonema adriaticum Kützing, 1844 (M)
R. arcuatum Kützing, 1844 (M)

Rhopalodiaceae (Karsten) Topachevs'kyj & Oksiyuk, 1960
Epithemia turgida (Ehrenberg) Kützing, 1844 (F)

Stauroneidaceae D.G.Mann, 1990
Stauroneis africana Amossé, 1934
S. spicula Hickie, 1874 (M)

Striatellaceae Kützing, 1844
Grammatophora oceanica Ehrenberg, 1840 (M)
Striatella unipunctata (Lyngbye) C.Agardh, 1832 (M)

Surirellaceae Kützing, 1844
Campylodiscus fastuosis Ehrenberg, 1845(M)
Surirella fastuosa (Ehrenberg) Ehrenberg, 1843 (M)
S. ovata Ehrenberg, 1844 (1845) (F)
S. striatula Turpin, 1828 (M)

Tebellariaceae Kützing, 1844
Tabellaria fenestrata (Cleve) Skabichevskii, 1960 (M)

Thalassionemataceae Round, 1990
Thalassionema nitzschioides (Grunow) Mereschkowsky, 1902 (M)
Thalassiothrix delicatula Cupp, 1943 (M)
T. longissima Cleve & Grunow, 1880 (M)

DICTYOCHOPHYCEAE (Silva, 1980)

DICTYOCHALES Hæckel, 1894

Dictyochaceae Lemmermann, 1901
Dictyocha sp.

DINOPHYCEAE (G.S.West & Fritsch, 1927)

DINOPHYSALES (Lindemann, 1928)

Amphidomataceae Sournia, 1984
Amphidoma steinii Schiller, 1929

Dinophysiaceae Stein, 1883
Dinophysis acuminata Claparède & Lachmann, 1859 (M) (T)
D. sacculus Stein, 1883 (M) (T)
D. ovum Schütt, 1895 sensu Martin, 1929 (M)
Dinophysis sp.

GYMNODINIALES Lemmermann, 1970

Gymnodiniaceae Lankester, 1885
Akashiwo sanguinea (K.Hirasaka) G.Hansen & Ø.Moestrup, 2000 (M, L)
Gymnodinium sp.
Gyrodinium spirale (Bergh) Kofoid & Swezy, 1921 (M)

Polykrikaceae Kofoid & Swezy, 1921
Polykrikos schwartzii Bütschli, 1873 (L)

PERIDINIALES Haeckel, 1894

Ceratiaceae Kofoid, 1907
Tripos furca (Ehrenberg) F.Gómez, 2013(M)

Gonyaulacaceae Lindemann, 1928
Alexandrium tamarense/catenella (Lebour, 1925) Balech, 1995 / (Whedon & Kofoid) Balech, 1985(M) (T)
A. minutum Halim, 1960 (M) (T)
Gonyaulax gracilis Schiller, 1935 (M)
G. jollifei Murray & Whitting, 1899 (M)
Lingulodinium polyedra (F.Stein) J.D.Dodge, 1989 (M)

Oxytoxaceae Lindemann, 1928
Corythodinium constrictum (Stein) F.J.R.Taylor, 1976 (M)
C. frenguelli (Rampi) F.J.R.Taylor, 1976 (M)
C. reticulatum (Stein) Taylor, 1976 (M)
Corythodinium sp.

Peridiniaceae Ehrenberg, 1831
Scrippsiella trochoidea (Stein) Loeblich III, 1976 (M)
Scrippsiella sp.

Protoperidiniaceae J.P. Bujak & E.H. Davies
Diplopsalis lenticula Bergh, 1881 (M)
Protoperidinium areolatum (Peters, 1928) Balech, 1974 (M)
P. bipes (Paulsen, 1904) Balech, 1974 (M)
P. brochii (Kofoid & Swezy, 1921) Balech, 1974 (M)
P. cassum (Balech, 1971) Balech, 1974 (M)
P. cerasus (Paulsen, 1907) Balech, 1973 (M)

P. decollatum (Balech, 1971) Balech, 1974 (M)
P. depressum (Bailey, 1854) Balech, 1974 (M)
P. globulum (Stein) Balech, 1974 (M)
P. hirobis (Abé, 1927) Balech, 1974 (M)
P. leonis (Pavillard, 1916) Balech, 1974 (M)
P. ovum (Schiller, 1911) Balech, 1974 (M)
P. parviventer Balech, 1978 (M)
P. pellucidum Bergh, 1881 (M)
P. punctulatum (Paulsen, 1907) Balech, 1974 (M)
P. quinquicorne (Abé, 1927) Balech, 1974 (M)
P. steinii (Jørgensen, 1899) Balech, 1974 (M)
P. tuba (Schiller) Balech, 1974 (M)
P. vulgare Balech, 1978 (M)
Protoperidinium sp.

Pyrophacaceae Lindemann, 1928
Pyrophacus horologium Stein, 1883 (M)

PROROCENTRALES Lemmermann, 1910

Prorocentraceae Stein, 1883
Prorocentrum arcuatum Issel, 1928 (M)
P. balticum (Lohmann) Loeblich, 1970 (M)
P. belizeanum M.A.Faust, 1993 (M)
P. dentatum Stein, 1883 (M)
P. emarginatum Y.Fukuyo, 1981 (M)
P. gracile Schütt, 1895 (M)
P. lima (Ehrenberg) F.Stein, 1878 (M) (T)
P. micans Ehrenberg, 1834 (M, L)
P. scutellum Schröder, 1900 (M)
Prorocentrum sp.

SUESSIALES (R.A.Fensome, F.J.R.Taylor, G.Norris, W.A.S.Sarjeant, D.I.Wharton & G.L.Williams, 1993)

Suessiaceae Montresor, Procaccini & Stoecker, 1999
Protodinium neapolitanum J.Schiller, 1928 (M)

EUGLENOPHYCEAE (Schoenichen in Eyferth & Schoenichen, 1925)

EUGLENALES Bütschli, 1884

Euglenaceae Dujardin, 1841
Euglena spirogyra Ehrenberg, 1832 (F)

CONJUGATOPHYCEAE Engler, 1892

DESMIDIALES C.E.Bessey, 1907

Closteriaceae Bessey, 1907
Closterium aciculare T.West, 1860 (F)

Zygnemataceae Kützing, 1843
Zygnema stellinum (O.F.Müller) C.Agardh, 1824 (F)

Appendix 2 Spearman correlations matrix between environmental factors and dominating microphytoplankton taxa (diatoms and dinoflagellates) in the water column. Values are in bold and underlined when significant with $p < 0.01$ and only in bold with $p < 0.05$

	Dino St.1	Diat St.2	Dino St.2	Diat St.3	Dino St.3	Other St.1	Other St.2	Other St.3	Av. temp.	Av. sal.	Av. oxy.	Chl. St.1	Chl. St.2	Chl. St.3	NH_4 St.1	NH_4 St.2	NH_4 St.3	NO_2 St.1	NO_2 St.2	NO_2 St.3	NO_3 St.1	NO_3 St.2	NO_3 St.3	PO_4 St.1	PO_4 St.2	PO_4 St.3	DIN St.1	DIN St.2	DIN St.3
Diat St.1	**<u>0,60</u>**	**0,83**	**0,69**	**0,78**	**0,70**	**0,61**	0,39	**0,49**	**0,58**	**0,61**	0,18	**0,45**	**0,59**	**<u>0,627</u>**	0,12	0,14	-0,08	**-0,41**	-0,39	**-0,44**	-0,31	-0,24	**<u>-0,56</u>**	**<u>0,58</u>**	0,38	0,25	0,02	0,04	-0,17
Dino St.1		**0,55**	**0,86**	0,40	**0,80**	**0,67**	**0,51**	**0,65**	**0,55**	**0,80**	-0,02	0,37	0,32	0,37	-0,05	-0,12	-0,30	**<u>-0,58</u>**	**-0,46**	**<u>-0,58</u>**	-0,29	**-0,44**	**<u>-0,51</u>**	**0,43**	0,18	0,11	-0,13	-0,29	-0,42
Diat St.2			**0,67**	**0,69**	**0,55**	**0,55**	0,32	**0,41**	0,37	**0,51**	0,08	**0,41**	**0,46**	**0,50**	0,21	0,21	0,09	-0,38	-0,32	-0,38	-0,26	-0,14	-0,39	**<u>0,60</u>**	**0,45**	**0,40**	0,08	0,15	0,05
Dino St.2				**0,46**	**0,90**	**0,78**	**0,55**	**0,71**	**0,65**	**0,78**	-0,20	**0,46**	0,34	0,37	0,01	-0,05	-0,34	**<u>-0,56</u>**	**-0,42**	**<u>-0,53</u>**	-0,21	-0,38	**<u>-0,52</u>**	**<u>0,58</u>**	0,28	0,15	0,02	-0,18	**-0,45**
Diat St.3					**0,51**	0,39	0,32	0,33	**0,53**	**0,42**	0,17	**0,64**	**0,64**	**0,57**	**0,40**	**0,44**	0,25	-0,31	-0,26	-0,37	0,05	0,004	**-0,40**	**0,55**	**0,44**	0,34	0,38	0,37	0,11
Dino St.3						**0,65**	**0,57**	**0,72**	**0,77**	**0,83**	-0,20	**0,47**	0,32	0,38	0,04	-0,04	-0,39	**<u>-0,58</u>**	-0,39	**-0,46**	-0,23	-0,34	**<u>-0,52</u>**	**0,49**	0,19	0,02	-0,01	-0,13	**-0,46**
Other St.1							**0,75**	**0,81**	**0,62**	**0,68**	0,09	**0,53**	**0,57**	**0,63**	0,11	0,07	-0,26	**-0,47**	**-0,57**	**-0,58**	-0,26	**-0,49**	**-0,63**	**0,50**	0,35	0,12	0,13	-0,13	**-0,43**
Other St.2								**0,84**	**0,60**	**0,56**	0,17	**0,69**	**0,52**	**0,48**	0,13	0,06	-0,21	**<u>-0,53</u>**	**-0,66**	**-0,55**	-0,13	-0,34	**<u>-0,46</u>**	0,32	0,30	0,02	0,11	-0,05	-0,32
Other St.3									**0,68**	**0,67**	0,004	**0,55**	**0,48**	**<u>0,55</u>**	-0,11	-0,15	**-0,42**	**<u>-0,58</u>**	**-0,56**	**-0,62**	-0,16	-0,37	**<u>-0,54</u>**	0,33	0,16	-0,01	-0,07	-0,23	**<u>-0,51</u>**
Av. temp.										**0,63**	-0,21	**0,61**	**0,53**	**0,41**	0,11	0,01	-0,27	**-0,42**	-0,35	-0,38	0,05	-0,25	**<u>-0,55</u>**	0,32	0,11	-0,19	0,22	-0,03	-0,39
Av. sal.											-0,20	0,26	0,33	**<u>0,52</u>**	-0,05	-0,09	**<u>-0,50</u>**	-0,38	-0,30	-0,34	-0,28	-0,35	**-0,44**	0,22	-0,01	-0,14	-0,07	-0,14	**-0,48**
Av. oxy.												0,27	0,29	0,38	0,27	0,33	**<u>0,51</u>**	-0,13	-0,30	-0,25	-0,25	-0,09	-0,23	0,31	**0,44**	**0,48**	0,05	0,18	0,34
Chl. St.1													**<u>0,65</u>**	**<u>0,63</u>**	**<u>0,61</u>**	**<u>0,56</u>**	0,33	**-0,47**	**-0,49**	**<u>-0,55</u>**	0,18	-0,04	-0,34	**<u>0,59</u>**	**<u>0,55</u>**	0,29	**<u>0,62</u>**	**0,43**	0,11
Chl. St.2															0,29	0,29	0,06	-0,29	**<u>-0,56</u>**	**-0,62**	0,03	-0,19	**-0,49**	0,34	0,21	-0,03	0,36	0,14	-0,09
Chl. St.3															0,20	0,33	-0,08	-0,29	**-0,42**	**-0,45**	-0,28	-0,32	**-0,44**	0,21	0,22	0,10	0,11	0,08	-0,16
NH_4 St.1																**<u>0,92</u>**	**<u>0,69</u>**	-0,13	-0,13	-0,11	0,03	0,04	-0,04	**0,45**	**0,58**	**0,44**	**0,83**	**0,73**	**0,51**
NH_4 St.2																	**<u>0,72</u>**	-0,02	-0,02	-0,09	0,04	0,12	0,03	0,40	**0,50**	0,41	**<u>0,75</u>**	**0,83**	**<u>0,54</u>**
NH_4 St.3																		0,13	0,16	0,10	0,24	0,36	0,25	0,20	0,41	**0,50**	**<u>0,56</u>**	**0,67**	**0,86**
NO_2 St.1																			**<u>0,75</u>**	**<u>0,80</u>**	0,28	**0,55**	**<u>0,62</u>**	**<u>-0,53</u>**	-0,29	-0,29	0,1	0,32	**0,43**
NO_2 St.2																				**<u>0,87</u>**	0,31	**0,56**	**0,65**	**-0,45**	-0,27	-0,10	0,04	0,32	**0,43**
NO_2 St.3																					0,17	**0,51**	**0,58**	**-0,47**	-0,18	-0,12	0,01	0,26	**0,41**
NO_3 St.1																						**<u>0,68</u>**	**0,51**	-0,27	-0,29	-0,28	**0,46**	0,31	0,32
NO_3 St.2																							**<u>0,77</u>**	-0,31	-0,23	-0,16	0,27	**<u>0,59</u>**	**<u>0,65</u>**
NO_3 St.3																								**<u>-0,61</u>**	**-0,40**	-0,23	0,11	**0,40**	**<u>0,58</u>**
PO_4 St.1																									**<u>0,83</u>**	**<u>0,71</u>**	0,30	0,15	-0,07
PO_4 St.2																										**<u>0,87</u>**	**0,42**	0,31	0,20
PO_4 St.3																											0,22	0,23	0,31
DIN St.1																												**<u>0,72</u>**	**0,47**
DIN St.2																													**<u>0,75</u>**
DIN St.3																													

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