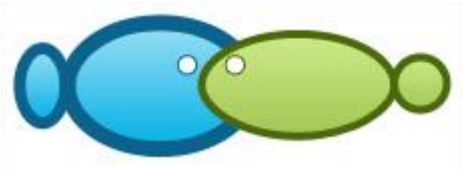

Environmental state of the Merja Zerga lagoon in Moulay Bousselham, Morocco: Metallic contamination levels and origins in sediments

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Abstract. The objective of this study is to contribute to the knowledge of the environmental status of the "Merja Zerga" lagoon in Moulay Bousselham by studying the level of metallic contamination (Cd, Pb, Hg, Cr, Ni, Cu, Zn and Fe) and the assessment of the sediment quality based on the enrichment factor (EF) and the two-sediment quality criteria TEC (Threshold Effect Concentration) and PEC (Probable Effect Concentration). To perform this work, 11 sampling stations were selected to cover the entire lagoon during the two seasons, summer 2016 and winter 2017. The granulometry of the sediments shows the predominance of a sandy facies downstream, with more than 93% arenites at the pass, while the upstream part is characterized by lutites with more than 98%. The organic matter contents show an almost homogeneous gradient, and they vary between 1.01% and 10.59% in summer and 1.02% and 11.39% in winter. The concentrations of Cd, Pb, Hg and Cu do not exceed the TEC threshold and do not show any noticeable effect for biota while the contents of Cr, Ni and Zn are moderate. Sediments can be considered as medium to poor quality. The results of this study show that the Merja Zerga Lagoon is an environment under anthropogenic pressure that can have an impact on the quality of its sediments and jeopardize its equilibrium and sustainability.
Key Words: metal contamination, sediments, enrichment factor, TEC, PEC, Merja Zerga.

Introduction. The "Merja Zerga" lagoon in Moulay Bousselham is considered among the most important protected areas of the Moroccan Atlantic coast, classified in 1978 as a "Permanent Biological Reserve" and in 1980 as a Ramsar site. This lagoon is a wetland with high biodiversity, consisting of a remarkable flora and fauna population of international value (Le Grusse et al 2014). The floristic potentialities are essentially phragmites, halophiles and submerged vegetation (Qninba et al 2006). The hydrological regime of the lagoon is influenced by the marine waters conditioned, by the tidal rhythm and the contributions of fresh water from Canal Nador and Ouad Drader. According to Bazairi (1999), the water level in the lagoon during low spring tide is higher than that of low neap tide. Furthermore, Labardi (2006) pointed out that the functioning of this ecosystem is complex, and experiences temporal instability governed by climatic factors and the permanent supply of continental waters.

The metallic trace elements known for their toxicity are derived from the geochemical bottom background and anthropogenic inputs. They are present in all compartments of the environment and 80% are resulted from the physical and chemical alterations of the rocks (Gouzy & Ducos 2008). The granulometry is one of the most important descriptive parameters that allow the interpretation of contaminant concentrations in the sediment to be refined. It helps to explain the natural variability of trace elements in sediments. Indeed, the greater the percentage of fine particle size fractions in the sediment (<63 µm), the greater the sediment's capacity to adsorb contaminants (Jaffé & Walters 1977).Agricultural practices, industrial and urban activities are at the origin of

anthropogenic contributions of metallic trace elements in marine ecosystems (Devallois 2009). When trace metals elements reach the aquatic environment, they constitute a major environmental problem. They are persistent and bio-accumulative pollutants that can lead to malfunctioning of all the links in the food chain because they are transmitted from one link to another through the consumption of contaminated aquatic organisms.

This study was conducted as part of the restoration of sensitive sites. The objective of the study is to assess the environmental quality of the Merja Zerga lagoon by determining the enrichment factor (EF) of the trace metals (Cd, Pb, Hg, Cr, Ni, Cu and Zn) in the sediment and by comparing the concentrations of the trace metals in the study area with the SQGs (Sediment Quality Guidelines) developed from biological and ecological effects that could be caused by certain concentrations of pollutants in the sediment. These are the TEC (Threshold Effect Concentration) and PEC (Probable Effect Concentration) established to assess marine and freshwater sediment quality (MacDonald et al 2000).

Material and Method

Description of the study sites. The "Merja Zerga" lagoon in Moulay Bousselham, is located on the Moroccan Atlantic coast between 34°48' and 34°53' north latitude and 6°19' and 6°16' west longitude (Figure 1). Elliptical in shape, the lagoon covers an area of 35 Km², with a maximum length of 9 Km and a width that does not exceed 5 Km. According to Kraïem et al (2001) the depth of the lagoon varies between 0 and 2 m (on average 50 cm) depending on the tidal cycle and rainfall.

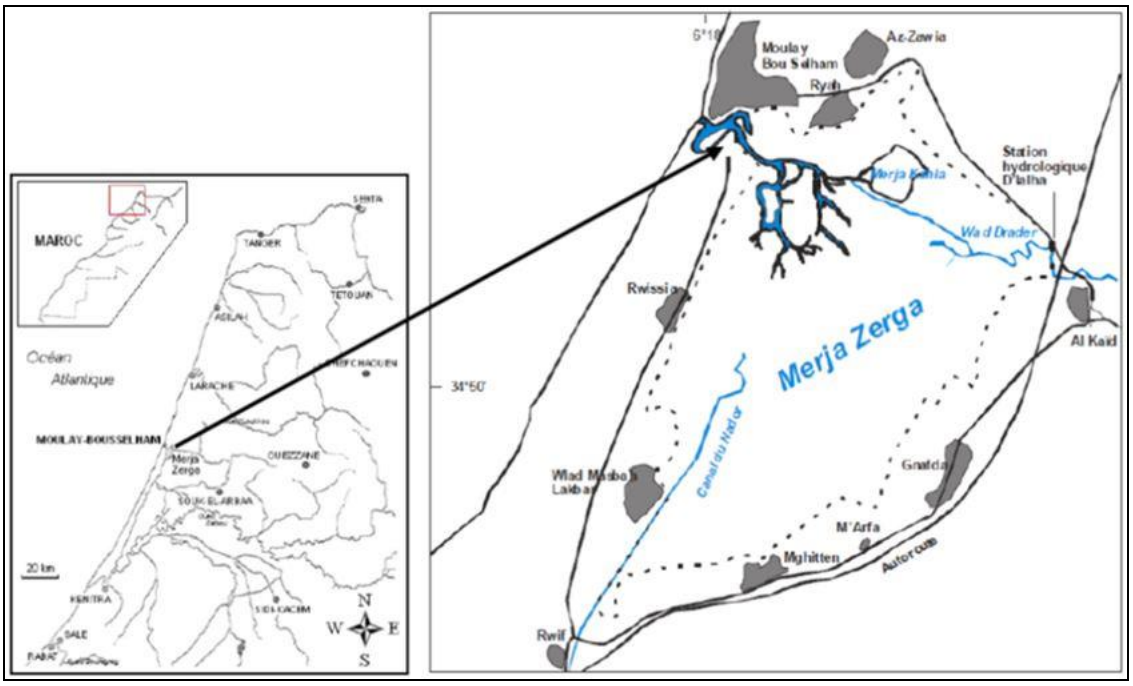

Figure 1. Geographical location of the Merja Zerga lagoon (Ramdani et al 2001).

Sampling methodology. Two sampling campaigns were carried out in the Merja Zerga lagoon during the dry and wet seasons in August 2016 and February 2017. They involved 11 sampling stations, with a total of 22 analysed samples. The coordinates of the sampling points were determined by GPS (Figure 2). The sediment samples were collected using a Van Veen Grab sediment sampler and placed in food-grade plastic bags, transported to the laboratory in coolers at approximately 4°C and stored in the freezer at -20°C until analysis.

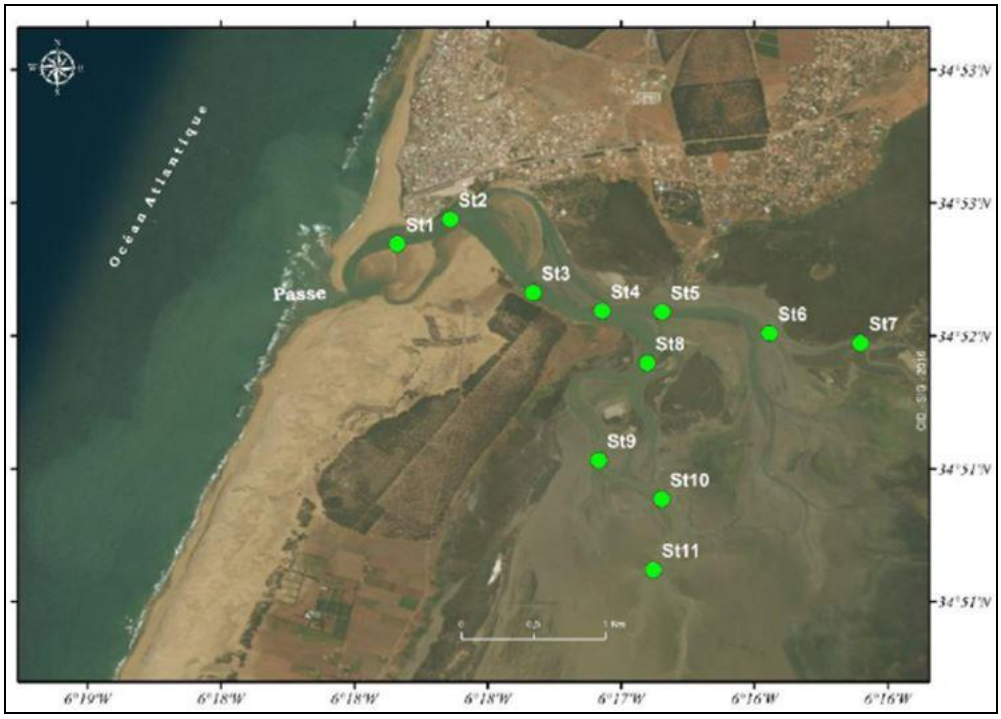

Figure 2. Location of sampling stations in Merja Zerga Lagoon.

Raw sediment treatment. For metallic trace elements analysis, the sediments were dried at 40°C in an oven. However, for the granulometry and organic matter analysis the sediments were dried at 150°C and the entire sample was treated. While for metallic trace elements, part of the sediment samples was sieved after homogenization by grinding with an agate mortar and pestle and only the fine fraction below 0.063 mm was retained for analysis.

Granulometry. The granulometry was determined out on raw sediments. The separation of the fine fraction from the sandy fraction was done by using a 0.063 mm mesh sieve. The substrate texture was evaluated from the weight percentage after sieving under running water on 2 mm and 0.063 mm sieves (Plumb 1981; CEAEQ 2003). The classification scale adopted is that of Wenthworth (Foucault & Raoult 1988):

- Rudites = fraction greater than 2 mm.
- Arénites (or sand) = fraction between 2 and 0.063 mm.
- Lutites (or mud) = fraction lower than 0.063 mm.

The granulometric analysis is carried out by dry sieving using a series of sieves (AFNOR 1994) from 2 mm to 0.063 mm (2 mm, 1.25 mm, 0.63 mm, 0.25 mm, 0.063 mm).

Organic Matter (OM). The method used for the determination of the organic matter in the sediment is incineration, "loss by calcination". The samples were placed in a muffle furnace at 375°C for 16 hours. The measurement of the mass lost, after the calcination, determine the quantity of organic matter contained in the sediment (CEAEQ 2003).
The results were calculated using the following equation:

$$\% (OM) = (\text{Dry sediment (g)} - \text{Incinerated sediment (g)} / \text{Dry sediment (g)}) * 100$$

Metallic trace elements. 200 mg of sediment prepared for analysis was mineralised in a microwave oven using a mixture of strong acids: 6 ml of HNO3 and 2 ml of HF in Teflon vials. The residue obtained after mineralisation was taken up in conical tubes by adding 0.8 g of H3BO3. Bi-distilled water was added to the solution to reduce the final volume to 50 ml (OSPAR/JAMP 2002). The analysis of the trace metals (Cd, Pb, Cr, Ni, Cu, Zn and Fe) was carried out by an ionization plasma coupled mass spectrometer (ICP-MS for Inductively Coupled Plasma - Mass Spectrometer brand Thermo iCAP Q Series) and the

total mercury (Hg) content in the sediment was determined by atomic absorption spectrophotometry using a direct mercury analyzer DMA-80 Milestone brand. A certified reference material (IAEA-158) and a blank were analyzed with each set of samples and are used for quality control and reliability of results.

Enrichment Factor (EF). Enrichment is an increase in total levels, following anthropogenic inputs, without prejudice to a negative evolution in the quality of the environment (Chassin et al 1996). According to Roussiez et al (2005), the enrichment factor (EF) provides information on the increase in the concentration of a chemical element in a sediment compared to a reference whose concentrations are little or not affected by anthropogenic phenomena. The reference elements most used to calculate the EF are Al, Li, Sc, Cs, Fe (Roussiez et al 2005; Hissler & Probst 2006).

In this study, the different enrichment factors of the trace metals in sediments were calculated using iron as the reference element. The concentrations of trace metals in the continental crust (Wedepohl 1995) were chosen as the geochemical background. The enrichment factor is calculated according to the equation given by (Sutherland 2000) using the annual average trace metal concentrations at each study station:

$$FE = (C_M / C_{Fe}) \text{ X } (CR_{Fe} / CR_M)$$

where:

C_M = concentration of element M in the sample,
C_{Fe} = concentration of iron in the sample,
CR_M = concentration of element M in the geochemical background,
CR_{Fe} = iron concentration in the geochemical background.

According to MacDonald et al (2000) and Sutherland et al (2000) five enrichment classes have been defined:

- EF < 2 no or low enrichment.
- 2 < EF < 5 moderate enrichment.
- 5 < EF < 20 significant enrichment.
- 20 < EF < 40 very high enrichment.
- FE > 40 extreme enrichment.

Environmental quality of sediments. The use of quality criteria demonstrated by MacDonald et al (2000), Burton (2002) and Desrosiers et al (2010), combining the chemical analyses with the ecotoxicological tests, allows a rapid assessment of the potential risk of the sediment studied. In the present study two quality criteria are chosen, the TEC and the PEC established by MacDonald et al (2000). The TEC identifies contaminant concentrations below which sediment-dwelling organisms are not affected, whereas the PEC identifies contaminant concentrations above which adverse effects on sediment-dwelling organisms are observed. Concentrations between TEC and PEC may occasionally have adverse effects on organisms.

Statistical treatments. The concentrations of trace metals in the sediment can be related to the content of fine fraction (<0.063 mm) or organic matter, Pearson correlation coefficient and principal component analysis (PCA) were performed, using R software (RCore-Team 2020), to classify the stations into groups that share the same geochemical characteristics.

Results and Discussion

Granulometry. The granulometry of the sediments at the lagoon level shows the predominance of a sandy facies downstream. More than 93% of its components are arenites at the fishway, generally represented by fine sands, with a decreasing gradient from the fine fraction (lutite < 0.063 mm) of the shoreline (1.90 to 1.83%) to the most continental upstream zone (97.75 to 98.61%) of the lagoon. One encounters successively rudite sands (St1), representative of the marine influence, muddy sands in the central

part of the lagoon, and mud in the area fed by the Nador canal waters (St10 and St11). A seasonal effect was noticed especially for the stations St6, St7 and St8 in the center of the lagoon and near Drader River for which the contents of the fine fraction pass successively from 23.3%, 16.9% and 19.0 % in summer (figure 3) to 41.9%, 46.5% and 70.7% in winter (figure 4). The results of previous studies, carried out on the same lagoon, showed that the contents of fine fraction upstream of the lagoon were of the order of 75 to 80% (Labardi 2006), and of the order of 70% (Alaoui et al 2010). Compared to these previous studies, our results show higher fine fraction contents. Indeed, this difference could be attributed to a change in the hydrodynamic functioning of the lagoon and/or to the continental inputs, via the Nador canal and Drader River, in fine sediment during the last ten years.

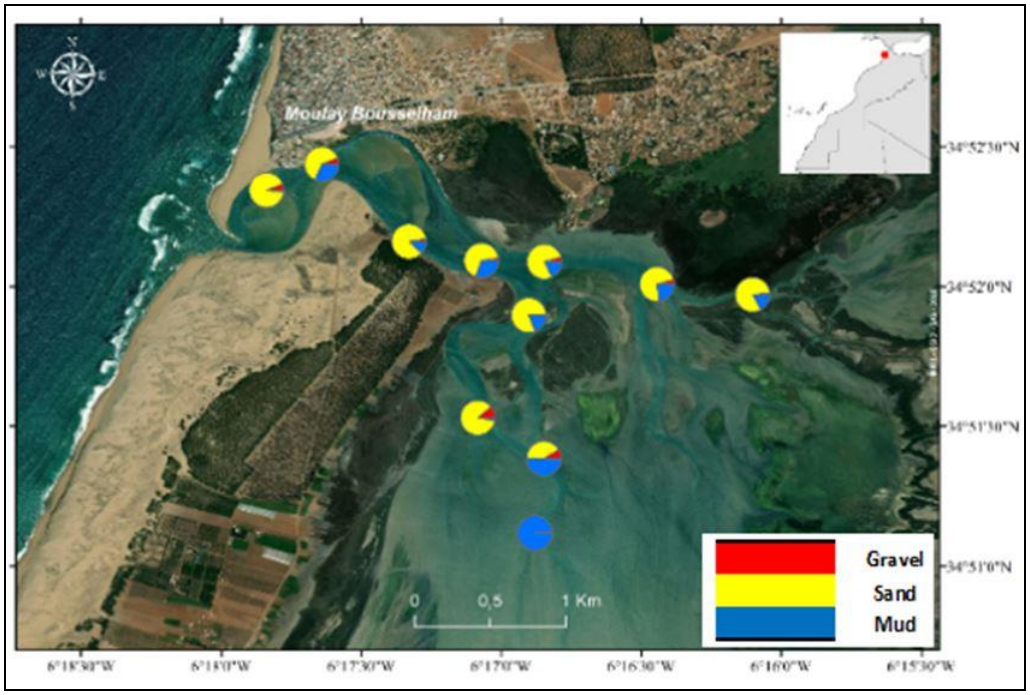

Figure 3. Granulometric distribution in the Merja Zerga lagoon in summer 2016.

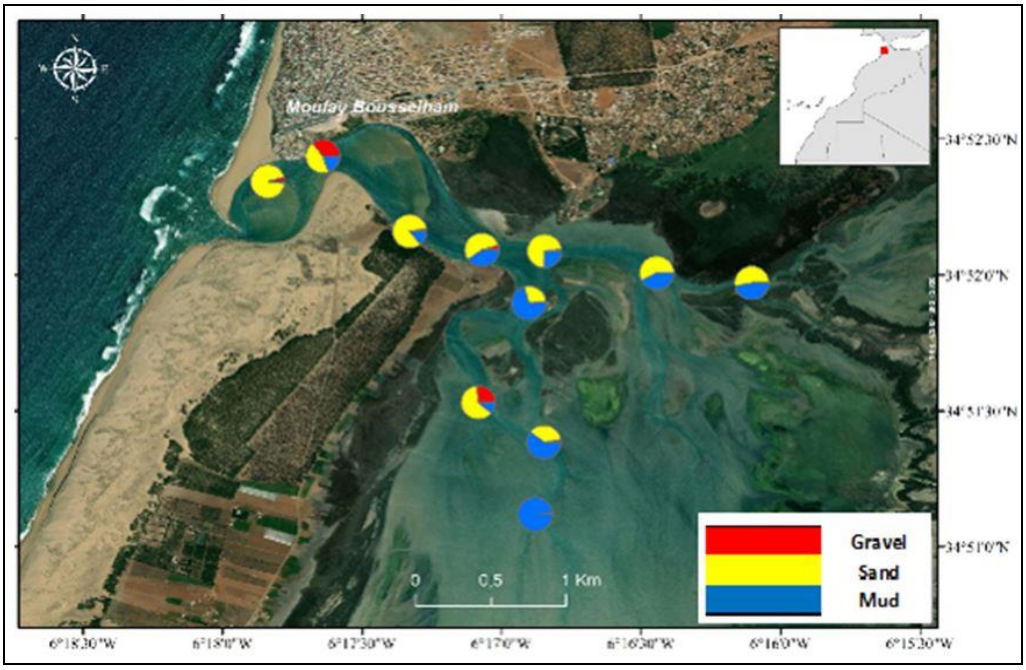

Figure 4. Granulometric distribution in the Merja Zerga lagoon in winter 2017.

Organic matter. During the study period, the analysis of organic matter in the lagoon of Merja Zerga shows an increasing gradient from downstream to upstream of the lagoon. The contents vary between 1.01% and 10.59% in summer (Figure 5) and 1.02% and 11.39% in winter (Figure 6). Overall, the organic matter content in the lagoon follows the distribution of lutites. These contents are low at the St1 station (point of contact with the sea) where 1.01% was recorded in summer and 1.02% in winter. This may be due to the strong agitation which does not allow the sedimentation of the fine fraction and consequently, the non-sedimentation of the organic matter. In the upstream part, the two stations St10 and St11, near the Nador canal, record the highest concentrations, respectively 5.85% and 10.59% in summer and 7.60% and 11.39% in winter. This part of the lagoon is characterized by currents and low depths that promote sedimentation. In addition, a temporal variation was noted for the contents of organic matter in the stations St6, St7 and St8, the values pass successively from 3.52%, 3.58% and 2.98% in summer to 5.80%, 7.23% and 7.64% in winter. Previous studies on the lagoon have recorded concentrations almost like our results with average concentrations upstream of the lagoon varying from 6 to 7% (Labardi 2006).

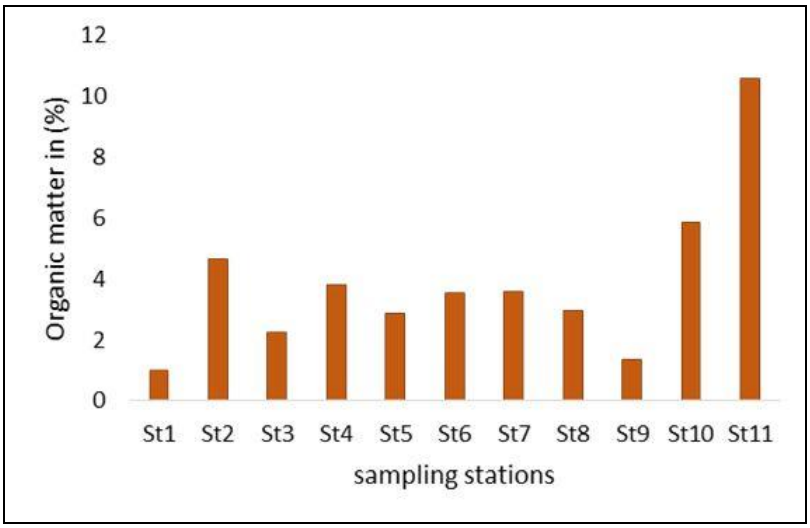

Figure 5. Organic matter distribution in the Merja Zerga lagoon in summer 2016.

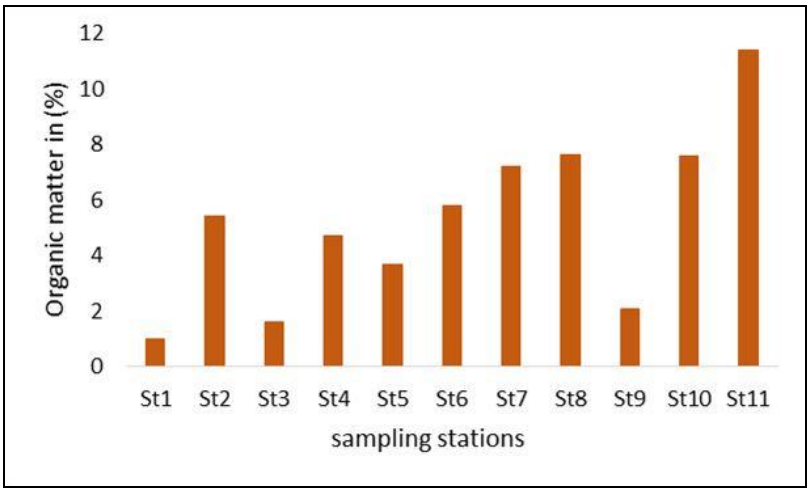

Figure 6. Organic matter distribution in the Merja Zerga lagoon in winter 2017.

Trace metal elements. For quality control and reliability of the results, a certified reference material (IAEA-158) was analyzed with each series of analysis and the results obtained are compared to the certified values (IAEA-158) (Table 1). The results in Table 2 show that the spatial distribution of TMEs is variable and the concentrations do not show an upstream-downstream gradient in the lagoon. The maximum levels of Cd, Hg,

Cr and Cu are recorded at St11 near Canal Nador for both seasons. Similarly, maximum values of 17.3 mg kg^{-1} and 129.82 mg kg^{-1} are recorded for Pb and Zn respectively at St11 in summer, while maximum levels of 22.3 mg kg^{-1} for Pb and 146.32 mg kg^{-1} for Zn are recorded at St3 in winter. However, an exception was underlined for Ni for which the maximum values of 84.84 mg kg^{-1} and 54.07 mg kg^{-1} are recorded respectively in summer and winter at the level of St1 downstream of the lagoon, which could be due to a contribution via marine waters. Indeed, similar results have been observed in the waters of the coastal fringe of the eastern Mediterranean of Morocco, which could suggest a transfer of micropollutants by the currents (Benedicto et al 2011).

Table 1

Measured and certified values of trace metals (mg kg^{-1}) in standard (IAEA-158) certified sediment

	Measured Values	*Certified Values*
Cd	0.38 ± 0.03	0.372 ± 0.039
Pb	37.4 ± 0.3	39.6 ± 4.7
Hg	0.129 ± 0.01	0.132 ± 0.014
Cr	75.8 ± 3.2	74.4 ± 5.8
Ni	32.06 ± 0.5	30.3 ± 2.9
Cu	49.58 ± 1.1	48.3 ± 4.2
Zn	157.9 ± 7.8	140.6 ± 9.5

The Threshold Effect Concentration (TEC) and Probable Effect Concentration (PEC) thresholds used show that the sediments in the Merja Zarga lagoon are of good to medium quality for Cd, Pb, Hg, Cu and Zn. However, for Cr and Ni the sediments are of average quality. The sediments of the downstream station St1 and the upstream station St11 are of poor-quality regarding Ni and Cr respectively (Table 2). These results corroborate those highlighted by Fouad et al (2019), this author has noted that the Moulay Bousselham lagoon is in a state of disturbance and its population is unbalanced.
Compared to previous studies conducted on the lagoon, the results of the present study are much lower than those recorded by Alaoui et al (2010) and Maanan et al (2013) (Table 3). It should be noted that considerable efforts have been made over the last decade in terms of remediation and wastewater treatment in the large agglomerations (Kénitra, Fes) which discharged wastewater into the waters of Sebou River, part of which flows into the lagoon via Nador canal. These results can be related to those published in 2015 by El Qoraychy on the Nador canal and the Merja Zerga (El Qoraychy et al 2015) and the results highlighted by Ben Yahkoub et al in 2019 on the Nador canal and the Gharb region (Ben Yahkoub et al 2019). We should also note the drop-in activity in the rice fields near the lagoon since 2009. This agricultural activity had a great impact on the quality of the lagoon's soils and sediments (Maanan et al 2013).

Table 2

Comparison of concentration of trace metals in sediment with toxicological reference values in summer (Sum) and winter (Wint) (Cd, Pb, Hg, Cr, Ni, Cu, Zn in mg kg^{-1} dry weight)

Studied sites	*Cd*		*Pb*		*Hg*		*Cr*		*Ni*		*Cu*		*Zn*	
	Sum	*Wint*	*Sum*	*Wint*	*Sum*	*Wint*	*Sum*	*Wint*	*Sum*	*Wint*	*Sum*	*Wint*	*Sum*	*Wint*
St1	0,14	0,16	7,73	22,1	0,002	0,002	26,43	62,37	84,84	54,07	9,49	21,49	49,48	81,1
St2	0,16	0,11	15,67	16,31	0,022	0,018	92,1	25,64	46,54	20,7	22,14	13,56	112,47	74,53
St3	0,14	0,17	14,85	22,3	0,021	0,017	92,18	49,74	43,51	28,92	18,85	18,65	103,71	146,32
St4	0,1	0,14	14,85	16,2	0,022	0,018	98,36	51,97	38,89	29,56	20,33	15,08	108,22	84,73
St5	0,11	0,1	15,69	15,8	0,015	0,017	68,06	48,36	34,44	27,69	15,29	15,26	87,02	84,43
St6	0,13	0,09	14,25	12,41	0,02	0,022	87,91	44,28	42,24	18,98	16,43	11	95,31	59,89

St7	0,07	0,1	14,38	13,9	0,023	0,025	33,54	46,84	26,42	23,04	15,22	14,01	84,13	69,73
St8	0,12	0,15	14,87	14,19	0,019	0,022	55,53	36,1	31,81	27,68	17,8	13,88	93,92	82,11
St9	0,1	0,18	9,87	18,89	0,016	0,02	31,59	82,17	23,44	33,71	11,91	20,14	65,82	101,53
St10	0,14	0,1	14,48	15,73	0,02	0,025	55,48	59,17	31,18	26,9	19,05	14,5	96,49	78,69
St11	0,22	0,18	17,13	20,68	0,027	0,027	150,91	123,45	41,4	39,21	26,3	25,77	129,82	124,42
TEC*	0.99		35.8		0.180		43.40		22.70		31.60		121	
PEC**	4.98		128		1.060		111		48.60		149		459	

* TEC effect threshold concentration (mg kg^{-1} dry weight) (MacDonald et al 2000).
** PEC Probable effect concentration (mg kg^{-1} dry weight) (MacDonald et al 2000).

Table 3

Comparison of trace metals concentrations (mg kg^{-1} dry weight) in the Merja Zerga lagoon with previous studies

		The present study (2016-2017)	*Maanan et al (2013)*	*Alaoui et al (2010)*
Cd	Min	0.07	0.00	0.02
	Max	0.22	1	0.84
Pb	Min	7.73	13.5	6.2
	Max	22.30	58	31.7
Hg	Min	0.00	0.00	0.02
	Max	0.03	0.7	0.61
Cr	Min	25.64	18	18.9
	Max	150.91	120	113
Ni	Min	18.98	15.5	10.5
	Max	84.84	72	96
Cu	Min	9.49	13.5	22
	Max	26.30	197	310.7
Zn	Min	49.48	100	167
	Max	146.32	410	758.9

The enrichment factor is a tool to determine whether the concentrations of TECs obtained in soils are anthropogenic or natural (Nga et al 2016). In this study, the different enrichment factors for the mean annual trace metals in sediment for each station were calculated using Fe as the reference element. Trace metal element concentrations in the continental crust were chosen as the geochemical background (Wedepohl 1995). The (EF) calculated relative to annual means are shown (Table 4).

The sediments of the Merja Zarga lagoon are not enriched in Pb and Hg since the EFs in the lagoon sediments for these two metals are less than 2, except for St11 for which the EF is 2.60 for lead. For Cd and Cu, the results vary from low to moderate enrichment, with the highest values recorded at the St11 level with 4.63 for Cd and 4.24 for Cu. For Cr, Ni and Zn moderate to significant enrichment is found in almost all lagoon sediments, with enrichment factors in the St11 at 9.14 for Cr, 5.06 for Ni and 5.71 for Zn. The highest values of EF in ST9, St10 and St11, which are close to the Nador canal one of the main emissaries that drain the surge water from the Gharb plain to the lagoon, indicate that these three stations have had the highest anthropogenic inputs compared to the other stations (Alaoui et al 2010). Indeed, the study conducted by Lagliti et al (2019) highlights the impact of the Nador canal on the lagoon and place its waters in the poor to very poor class. This confirms the risk of contamination on the lagoon despite the great efforts made in the depollution and treatment of water from this emissary.

Table 4

Sediment enrichment factor in the Merja Zerga lagoon for the elements (Cd, Pb, Hg, Cr, Ni, Cu and Zn) and average Fe concentrations in mg g-1 dry weight

Studied sites	*Cd*	*Pb*	*Hg*	*Cr*	*Ni*	*Cu*	*Zn*	*Fe average concentration*
St1	1.08	0.64	0.02	0.92	2.71	0.79	0.91	42.48
St2	1.60	1.12	0.43	2.01	2.16	1.49	2.15	25.84
St3	1.95	1.37	0.43	2.54	2.44	1.64	3.01	24.66
St4	1.63	1.24	0.49	2.92	2.50	1.68	2.52	22.75
St5	1.74	1.51	0.48	2.71	2.72	1.74	2.69	18.96
St6	1.80	1.29	0.62	3.12	2.72	1.58	2.46	18.72
St7	1.42	1.40	0.72	1.94	2.24	1.72	2.49	18.32
St8	2.33	1.52	0.65	2.33	2.85	1.97	3.02	17.33
St9	2.58	1.58	0.60	3.04	2.87	2.09	3.01	16.54
St10	2.31	1.75	0.78	3.23	3.08	2.31	3.32	15.66
St11	4.63	2.60	1.13	9.15	5.06	4.25	5.71	13.22
UCC*	0.1	17	0.056	35	18.6	14.3	52	30890

* Trace metals elements contents in (μg g^{-1}) in continental crust (Wedepohl 1995).

Statistical analysis. A statistical analysis was performed to quantitatively identify specific areas of contamination. The Pearson correlation matrix (Table 5) shows a good correlation between Cd, Pb, Cr, Cu and Zn on the one hand, and between Hg, Cr, Cu, the fine fraction, and organic matter on the other. A significant correlation ($p<0.05$) between these elements probably indicates their common origin.

Table 5

Correlation matrix (Pearson)

Variables	*Cd*	*Pb*	*Hg*	*Cr*	*Ni*	*Cu*	*Zn*	*FF*	*MO*
Cd	1								
Pb	0,756	1							
Hg	-0,015	0,225	1						
Cr	0,737	0,724	0,474	1					
Ni	0,473	0,179	-0,801	0,049	1				
Cu	0,842	0,857	0,404	0,909	0,138	1			
Zn	0,666	0,909	0,539	0,774	-0,154	0,836	1		
FF	0,389	0,393	0,694	0,741	-0,221	0,708	0,517	1	
MO	0,297	0,330	0,736	0,677	-0,281	0,656	0,450	0,976	1

Principal Component Analysis (PCA) is performed on a data matrix consisting of 22 samples (11 stations x 2 campaigns) during which nine elements were measured. The percentage of inertia, expressed by the first two axes, explains more than 85.77% of the variance, including 59.81% for F1 and 25.97% for F2.

The main F1 axis is characterized in positive by Cr (r0.93), Cu (r0.96), Zn (r0.88), Pb (r0.81), Cd (r0.72), Hg (r0.60), organic matter (r0.78) and the fine fraction (r0.82) with ($p<0.05$) (Figure 8) graph A. In the light of these results, it appears that the F1 axis defines an axis of metallic pollution of anthropogenic origin. Moreover, Ni (r0.90) is very significantly correlated with the F2 axis ($p<0.05$).

The distribution of sampling points on either side of the F1 axis shows the existence of three groups (Figure 8) graph B. The first group consists of St1 (downstream stations), loaded with nickel. The second group includes the central stations of the lagoon (St2, St3, St4, St5, St6, St7, St8, St9, St10), slightly to moderate contaminated. The

third group represents the stations upstream of the lagoon (St11). This station is characterized by significant contamination of anthropogenic origin. These statistical results confirm the observations already made regarding the quality of the lagoon sediment based on the threshold effect concentration (TEC) and probable effect concentration (PEC) thresholds and on the enrichment factor (EF).

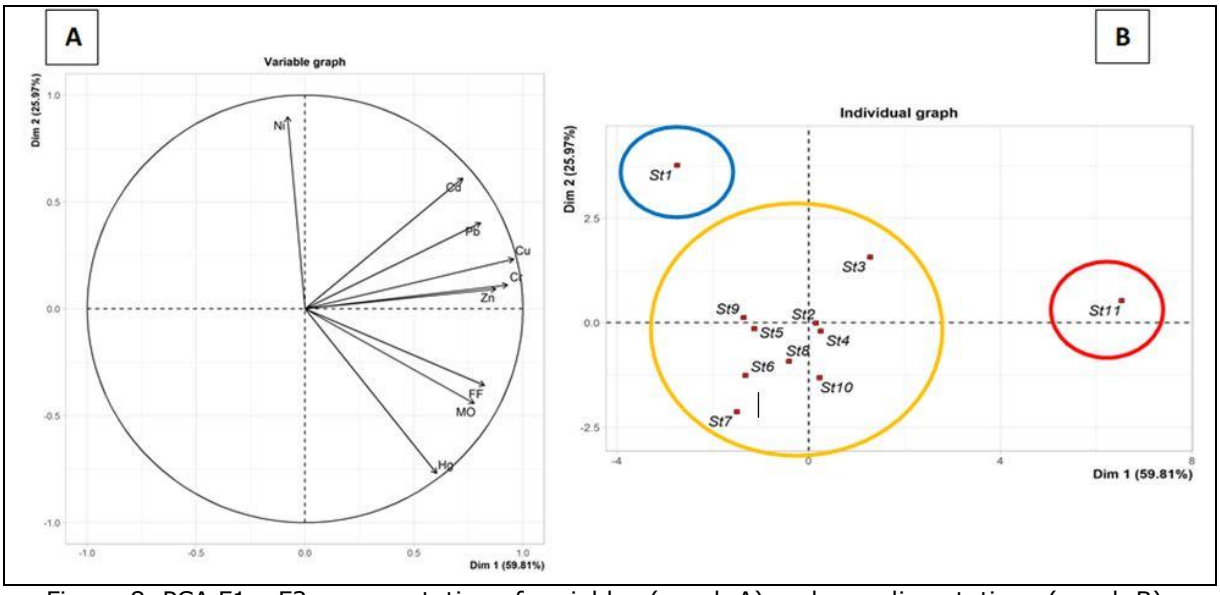

Figure 8. PCA F1 x F2 representation of variables (graph A) and sampling stations (graph B).

Conclusions. From these results, it appears that the granulometric study of the sediments collected from the Merja Zerga lagoon has revealed the presence of three sedimentary facies: a sandy facies, a sandy-muddy facies and a muddy facies. Organic matter levels in the lagoon follow the distribution of lutites. These contents are low downstream of the lagoon and more important upstream.

From the downstream to the upstream side of the lagoon, the evolution of metallic pollution in the sediments shows the existence of three zones:

- A first zone loaded with Nickel, which requires studies on the level of Ni contamination in the coastal areas of the lagoon to be able to confirm the oceanic contribution of this element in the lagoon,
- A second area of good to average quality, spread over the entire central part of the lagoon following the efforts made in the remediation and treatment of wastewater discharged into the waters of Nador Canal, and which drains the thrust water from the Gharb plain to the lagoon,
- A third area upstream of the lagoon characterized by significant contamination of anthropogenic origin, and which requires more effort in terms of treatment of the water discharged into the lagoon.

In the end, the Merja Zerga lagoon remains a fragile ecosystem that is under anthropogenic pressure from trace metals, which is manifested in the quality of the lagoon's sediments.

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Received: 21 July 2020. Accepted: 14 September 2020. Published online: 14 March 2021.
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How to cite this article:
Anhichem M., Benbrahim S., Idrissi M., Chfiri R., Yahyaoui A., 2021 Environmental state of the Merja Zerga lagoon in Moulay Bousselham, Morocco: Metallic contamination levels and origins in sediments. AACL Bioflux 14(2):774-785.