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Concept Paper

The Marine Influence Index (MII): a tool to assess estuarine intertidal mudflat environments for the purpose of foraminiferal biomonitoring

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Abstract: In this paper, we propose a Marine Influence Index (MII), which is thought to give an integrated quantitative description of the complex of environmental parameters controlling foraminiferal faunas in estuarine intertidal mudflats. The MII contains three components: 1) the relative distance along the salinity gradient, 2) the emergence time relative to a reference tidal cycle, and 3) the relative importance of river outflow in the 30 days before sampling the foraminiferal faunas. Although these three parameters have all a strong relation with salinity, they implicitly also include other environmental parameters, like the introduction of marine and continental organic matter and biota, hydrodynamic energy, or temperature. To show the functioning of this new index, MII is calculated for 28 stations in the Auray and Vie estuaries, for two different periods. The next step will be to compare the MII with faunal data sets. Ideally, this comparison should allow us to find strong correlations between some characteristics of the foraminiferal assemblages and MII. If such strong correlations would indeed be found, any major deviation of this relationship could then be interpreted as due to strong anthropogenic disturbance.

Keywords: estuaries; bio-monitoring; foraminifera; anthropogenic impact; pollution

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Supplementary online material

1. Methodology for estimating absolute altitude and emergence time

The absolute altitude of each sampling station was estimated with respect to the French chart datum, i.e. the elevation (in meters) above the lowest astronomical tide.

For stations located in the lowest part of the intertidal flat, that were sampled at low tide immediately above the water table, the level of the low tide on the sampling day was considered as the altitude of the sampling point. For this purpose, we used the tidal curves published by the French Naval Hydrographic and Oceanographic Service (SHOM). For all other sampling stations, the altitude was estimated by means of an electronic theodolite (NA720 ® Leica; height accuracy < 1cm) referenced to official altitude benchmarks installed by the National Institute of Geographic and Forest Information (IGN; https://geodesie.ign.fr/). When stations were located too far from referenced benchmarks, the lichen vertical zonation (https://www.marlin.ac.uk), well developed on rocky outcrops and walls (like quay, jetty, wharf..), was used. The conspicuous upper limit of the black lichen *Verrucaria maura* typically covers the entire rock surface, giving a distinct black band in the upper littoral fringe. This limit corresponds to the mean highest spring tide water, for which the elevation is given in the tide tables of the SHOM. Furthermore, this limit is highlighted by the lower limit of the orange lichen *Xanthoria parietina*, that marks the beginning of the supratidal zone.

Tidal curves available from the SHOM (https://maree.shom.fr/) are issued from the TELEMAC-3D code included in the TELEMAC-MASCARET modelling system, managed by a Consortium of 8 European organisations from France, Germany, and UK (http://www.opentelemac.org). For the Auray estuary, validation of the model output is made by comparison of the predicted water levels with in situ observations of sea level from the tide gauge located at the entrance of the Morbihan Gulf, Le Crouesty Harbour. This mathematical modelling, taking into account the tidal asymmetry (i.e. distortion of the tidal wave entering and propagating upstream the estuary), gives us access to corrected tidal curves for 4 locations regularly spaced along the river: at the river mouth (Port Navalo) and at 2.8, 8.0 and 15.0 km from the entrance (Locmariaquer, Fort-Espagnol, and Auray, respectively). For these locations, SHOM has calculated the altitude of the tidal reference levels (Supplementary Table S1). In the constricted Vie estuary, where mathematically calculated curves are not available, we used the tidal curves and associated reference levels calculated for the St. Gilles harbour (about 1 km from the mouth of the estuary).

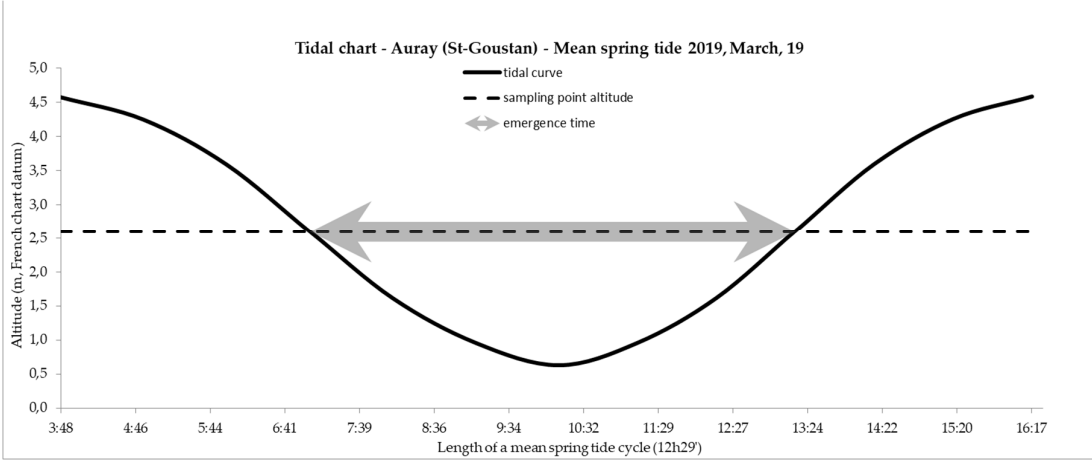
Considering all the field constraints, instrumental accuracy, and errors in estimated tide levels, we estimate a range of uncertainty of +/- 10 cm for our elevation data.

Supplementary Table S1. Tidal reference levels for St. Gilles Croix de Vie (Vie estuary) and four sites in the Auray estuary: Port Navalo (mouth of the estuary), Locmariaquer (2.8 km from the mouth), Fort-Espagnol (8.0 km from the mouth) and Auray (15.0 km from the mouth).

	Vie estuary	**Auray estuary**			
Tidal reference level (cm)	**St Gilles**	**Auray**	**Fort-Espagnol**	**Locmariaquer**	**Port Navalo**
Highest astronomical tide (HAT)	587	520	521	516	565
Mean high water springs (MHWS)	515	470	465	460	505
Mean high water neaps (MHWN)	415	365	365	365	400
Mean sea level (MSL)	317	276	278	276	305
Mean low water neaps (MLWN)	205	160	155	155	190
Mean low water springs (MLWS)	75	50	60	60	70
Lowest astronomical tide (LAT)	1	8	8	8	5
Distance to the sea (km)	1.0	15.0	8.0	2.8	0.0

The reference emergence time (ET, expressed as a fraction of total tidal cycle) has been calculated for each sampling point, on the basis of absolute altitude and the tidal curves, which are provided by SHOM for all French harbours [63].

In order to do so, on the mean spring tide curves, we measured the time lapse between the two moments when the tide level corresponded to the absolute altitude of the sampling point, during successive descending and ascending tides (Supplementary Figure S1). The duration of this time lapse was then divided by the total duration of the tidal cycle to obtain the reference emergence time expressed as a proportion.



Supplementary Figure S1. Schematic representation of the duration of emergence at a sampling point (arbitrary chosen at 2.6 m altitude) during a mean spring tide cycle, for the site Auray in the upper Auray estuary. In this example, the duration of emergence is 6h14'30'', whereas the tidal cycle takes 12h19'. The corresponding reference emergence time will be 50%.

We decided to use mean spring tide data (in France: tidal coefficient of 90) in order to be able to compare sites and because during spring tide, the whole intertidal mud flats are at least immerged part of the day.

2. Methodology to calculate RD/CS and RRO (Relative River Outflow)

River discharge (RD) values were obtained from the internet site http://www.hydro.eaufrance.fr/ of the French Ministry of Ecology, Sustainable Development and Energy, which gives for all major French rivers both yearly averages and daily values. A mean value was calculated for the 30 days preceding sampling.

The river cross section (CS) was determined on the basis of the widths and depths read on the nautical charts provided by the SHOM (https://data.shom.fr). For each locality, the cross section was calculated at high tide, by calculating the surface of polygons between points of known depth available on the maps. The total cross section was obtained by adding the surface of all polygons.

In order to contextualise the obtained RD/CS values, they were normalised into RRO (Relative river outflow) values by dividing them by 25 (multiplication with 0.04), which corresponds to the RD/CS value observed at the Cordemais site upstream in the Loire valley (Supplementary Figure S2; Supplementary Table S2). This locality is supposed to be the estuarine site with maximal river influence along the French Atlantic coast. To give more weight to differences at the lower end of the 0.0 to 1.0 scale, we used the square root of 0.04 RD/CS as our normalised RD/CS value.

3. RRO in the Loire estuary

In order to further illustrate the behaviour of RRO (Relative river outflow), this parameter has been calculated for four points in the Loire estuary (Supplementary Figure S2; Supplementary Table S2).



Supplementary Figure S2. Map of the Loire estuary with the position of the four localities used here.

Supplementary Table S2. RD/CS and RRO (relative river outflow) calculated for four sites in the Loire estuary, using an average yearly discharge volume (RD) of 854 m^3/s.

	Width estuary	Cross section	RD/CS	RRO (relative river outflow)
1. Cordemais	750 m	3400 m^2	25.15 cm/s	1.00
2. Paimboeuf	980 m	5150 m^2	16.57 cm/s	0.81
3. Donges	2750 m	11325 m^2	7.54 cm/s	0.55
4. St. Nazaire	1900 m	12950 m^2	6.59 cm/s	0.51

Supplementary Table S3. RD/CS and RRO (relative river outflow) calculated for four sites in the Loire estuary, using the discharge volume (RD) of 193 m^3/s, the average value measured during low water conditions in October 2019.

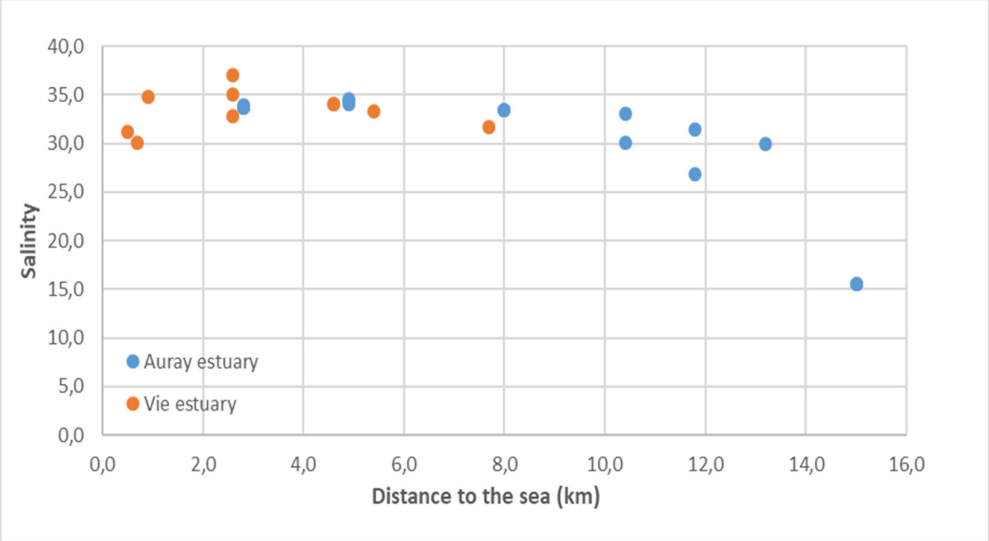
	Width estuary	Cross section	RD/CS	RRO (relative river outflow)
1. Cordemais	750 m	3400 m^2	5.68 cm/sec	0.48
2. Paimboeuf	980 m	5150 m^2	3.74 cm/sec	0.39
3. Donges	2750 m	11325 m^2	1.70 cm/sec	0.26
4. St. Nazaire	1900 m	12950 m^2	1.49 cm/sec	0.24

We can observe that, for average runoff conditions (854 m^3/s), the RRO decreases from 1.0 at Cordemais, in the inner estuary, to 0.51 at St. Nazaire, at the mouth of the estuary. For comparison, in Supplementary Table S3, we show the same data calculated for October 2019, when the average river discharge was only 193 m^3/s. During these low runoff conditions, RRO decreases to a range of 0.48 (at Cordemais) to 0.24 (at St. Nazaire).

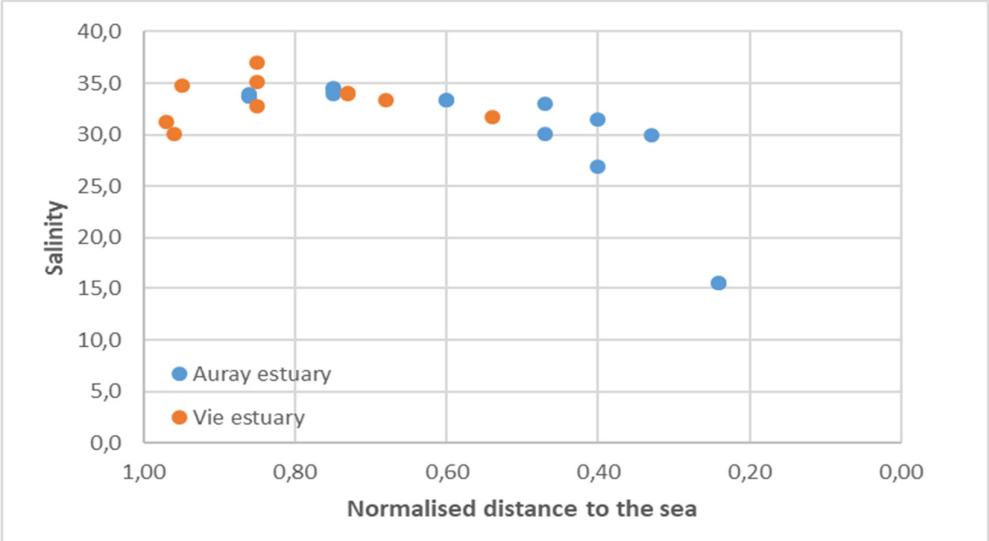
4. Relation between MII and salinity

MII is determined by three components: 1) the normalised distance to the sea, 2) the reference emergence time and 3) the relative importance of river outflow. In the two examples used in this paper, sampling took place in the dry summer season, when runoff

was minimal, and hardly influenced MII. Since emergence time depends mainly on altitude, this factor is only weakly related to salinity. Consequently, we expect to have a much stronger relation between salinity and distance to the sea than between salinity and MII. Furthermore, for Auray estuary, salinity measurements were made in July 2019, for the Vie estuary in June 2020, and not in October 2018, when MII was calculated. For all these reasons, we compare here our salinity measurements for the Auray and Vie estuaries with a) absolute distance to the sea (Supplementary Figure S3), and b) the normalised distance to the sea (Supplementary Figure S4; normalised to 1.0 with respect to the distance between the mouth and the farthest point of salt intrusion).



Supplementary Figure S3. Relation between measured salinity and distance to the sea for the Auray estuary (in blue, July 2019) and Vie estuary (in orange, June 2020).



Supplementary Figure S4. Relation between measured salinity and normalised distance to the sea for the Auray estuary (in blue, July 2019) and Vie estuary (in orange, June 2020).

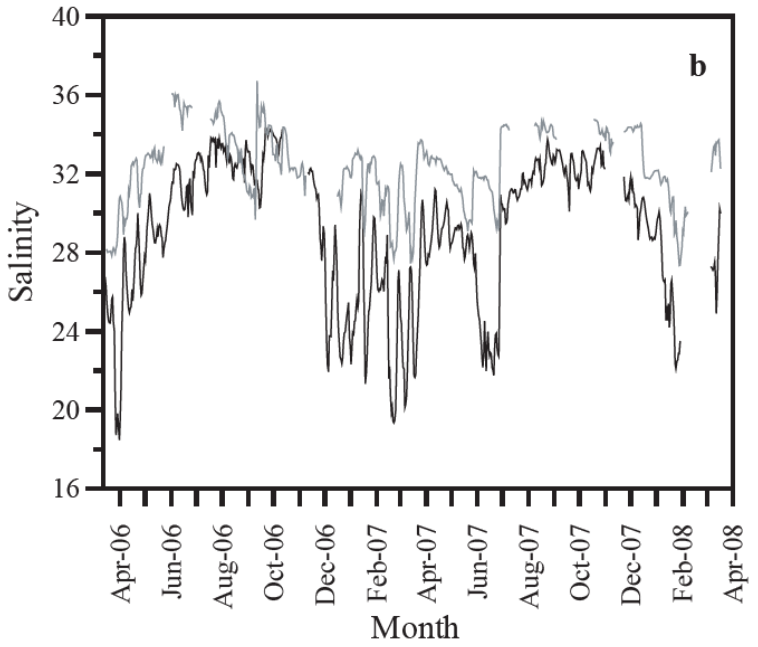
When interpreting these figures, several elements have to be kept in mind:

a) in both estuaries, at several sites, two or three stations were measured, at different altitude on the mudflat. The distance to the sea is the same, but salinity measurements yielded sometimes important differences. This was for instance the case in the Vie estuary at 2.6 km from the coast or in Auray estuary at 11.8 km from the coast (Supplementary Table S4). In such cases, at the points of higher elevation, salinity was measured in pools (at low tide), whereas the salinity of the lowest point was measured in the channel. In all cases, the salinity was higher at the point of higher elevation (Supplementary Table S4), where the high tide waters trapped in pools may become saltier due to evaporation during emergence. The overall salinity gradient is therefore best represented by the lowest points on the graphs.

b) salinity measurements were always made at low tide, but not exactly at the same moment of the tidal cycle. This may cause differences between sites.

When comparing the data for the Auray and Vie estuaries, it appears that a much more complete salinity gradient is present in the Auray estuary compared to the Vie estuary. In Auray estuary, a minimum salinity of 15.5 is measured 15.0 km from the sea (normalised distance 0.24), whereas in the Vie estuary, a minimum salinity of 31.7 is measured 7.7 km from the sea (normalised distance 0.54). The weaker salinity trend in the Vie estuary is due to the construction of a sluice at 8 km from the sea, so that only part of the salinity gradient is present. On Supplementary Figure S4, where salinity is plotted versus the normalised distance to the sea, the lowest measurements for both estuaries (made in the channel) perfectly overlap. This fully confirms the validity of our decision to use a value of 16.8 km as an estimate of the salt penetration in the Vie estuary before the construction of this sluice. This distance was used to calculate the normalised distances to the sea.

Finally, Supplementary Figure S4 shows a strong relation between salinity and the normalised distance to the sea, showing that this component of MII reliably translates the salinity gradient. However, the relationship between distance to the sea and salinity is highly dynamic, and changes considerably on a diurnal and seasonal scale, as is for instance shown by the data of Diz et al. [48] (Supplementary Figure S5), collected with a data logger at two sites in the Auray estuary, Locmariaquer (our site 1) and Bono (close to our site 5).



Supplementary Figure S5. Bottom water salinity (in the main estuarine channel) in Bono (black line) and Locmariaquer (grey line) between March 2006 and March 2008. After Diz et al. [48].

The consequence is that there will always be a relation between salinity and distance to the sea, but that the point where salinity rapidly slopes down (in Auray estuary in July 2019 between 12 and 15 km from the sea) will show considerable lateral shifts, on diurnal as well as seasonal time scales (Supplementary Figure S3). It is exactly for this reason that we consider single-time salinity measurements as non-representative, and inadequate for comparison with faunal data.

Supplementary Table S4. Comparison of MII, Altitude, Distance to the sea, Normalised distance to the sea and Salinity, for the Auray and Vie estuaries.

Auray	MII	Altitude (m)	Distance (km)	Normalised distance	Salinity
1A	0.48	2.5	2.8	0.86	33.7
1B	0.67	1.3	2.8	0.86	33.7
1C	0.65	1.4	2.8	0.86	33.9
2A	0.08	4.5	4.9	0.75	34.5
2B	0.17	4.2	4.9	0.75	34.4
2C	0.57	1.4	4.9	0.75	34.0
4A	0.25	3.3	8.0	0.60	33.4
4B	0.43	1.4	8.0	0.60	33.4
5A	0.28	2.2	10.4	0.47	33.0
5B	0.37	1.2	10.4	0.47	30.1
6A	0.21	2.5	11.8	0.40	31.5
6B	0.28	1.5	11.8	0.40	26.9
7	0.24	1.3	13.2	0.33	29.9
8A	0.13	2.3	15.0	0.24	15.5
8B	0.17	1.3	15.0	0.24	15.5
Vie	MII	Altitude (m)	Distance (km)	Normalised distance	Salinity
3	0.69	2.0	0.5	0.97	31.2
4	0.71	1.8	0.7	0.96	30.1
5	0.58	2.7	0.9	0.95	34.8
6	0.72	1.4	1.9	0.89	
7A	0.19	4.8	2.6	0.85	37.0
7B	0.31	4.2	2.6	0.85	35.1
7C	0.65	1.6	2.6	0.85	32.8
8A	0.26	4.2	4.6	0.73	34.1
8B	0.64	1.2	4.6	0.73	34.0
9	0.58	1.2	5.4	0.68	33.3
10A	0.11	4.9	7.7	0.54	
10B	0.36	2.2	7.7	0.54	31.7