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Assessment of river ecological status in the French West Indies based on diatom flora

Léonard Henry · Julie Guéguen · Sébastien Boutry · François Delmas · Estelle Lefrançois · Anne Eulin-Garrigue · Olivier Monnier · Juliette Tison-Rosebery

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Abstract The Water Framework Directive (WFD) requires member states to routinely assess the river ecological status using community-based indices. However, there is still a lack of published WFD-compliant methods for the French West Indies, especially using diatom-based indices. Martinique and Guadeloupe exhibit diverse landscapes shaped by their complex geological history and tropical climatic conditions. These strong particularities make the existing indices developed for the European mainland unusable. Based on diatom sampling from 2013 (607 samples) and through multivariate analyses, we developed the Indice Diatomique des Antilles (IDA). We first identified the key abiotic factors influencing

diatom communities on both islands, and then characterized taxon sensitivity by considering their presence probability along a pressure gradient. The index was based on the presence and relative abundance of these taxa in each sample. The last step consisted of using new data from the 2014–2022 sampling surveys (457 samples) as a validation dataset to verify IDA accuracy. Our results suggest that the IDA methodology is well designed to assess the ecological status of rivers in the West Indies.

Keywords Water Framework Directive · River ecological status · Diatoms · Biotic indices · French West Indies

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Introduction

The Caribbean islands are recognized as one of the most important global biodiversity hotspots, as they concentrate on numerous endemic species while undergoing exceptional habitat loss (Myers et al., 2000). These Islands contain at least 2% of the world's endemic plant and vertebrate species on only 0.4% of the Earth's land surface, and any damage to biodiversity in this region has accelerated global biodiversity erosion.

Among these islands, Martinique and Guadeloupe are particularly remarkable. As part of the West Indies, they have been shaped by intense volcanic activity since the Middle Eocene (49 Ma) (Graham, 2003). Composed of sedimentary limestone or magmatic rocks formed by the cooling of volcanic magma, the relief is highly variable. High, recently formed volcanoes give way to older reliefs and lowlands. This particular geography highly influences precipitation, as mountainous areas are exposed to intense rainfall, whereas coastal areas are drier. The complex geological origin of the Martinique and Guadeloupe islands, coupled with a tropical climate, created ecosystems with contrasting relief and pluviometry, leading to diverse habitats that support high biodiversity and endemism.

However, the expansion of agriculture, cities, and tourism has endangered this exceptional heritage. Freshwater habitats, including rivers, streams, lakes, and wetlands are particularly threatened by water pollution, flow modifications, species invasions, and over-exploitation of living resources (Lugo et al., 2012; Dudgeon, 2006; Dromard et al., 2016). To maintain or restore the ecological status of water bodies, and preserve the biodiversity they host, the development of aquatic ecosystem monitoring tools dedicated to these specific regions is crucial.

As part of the French overseas territories, the objectives of the Water Framework Directive (WFD, European Union, 2000) must be met in Martinique and Guadeloupe. However, there is still a lack of published WFD-compliant methods for the French West Indies, especially for community-based assessments of river quality (Bernadet et al., 2013). Existing indices dedicated to the European continent cannot be directly transposed due to biogeographic differences in community composition, as the development of bioassessment methods overseas has long

been hampered by the lack of knowledge on exotic fauna and flora (Carayon et al., 2019). Despite the fact that microalgae are recognized worldwide as relevant bioindicators (Leboucher et al., 2019; Soininen, 2007), diatom flora from the West Indies has remained particularly overlooked. Initial work was carried out by Bourrelly and Manguin (1952) who sampled rivers, mangrove areas, waterfalls, ponds, mosses, and seeps in Guadeloupe. Eight hundred species of algae have been described, including 124 diatom taxa from freshwater streams and waterfalls. No further investigation was undertaken until Coste and Dauta (1997) made the first freshwater diatom inventory of Martinique and Tudesque and Ector (2002) published the first atlas of Guadeloupe diatom flora. In the 2010s, little information on Guadeloupe and Martinique diatoms was available.

In this context, a 5-years research program (2009–2013) was used to establish the first diatom-based index dedicated to the ecological status assessment of rivers in Martinique and Guadeloupe (Lefrancois et al., 2019; JORF, 2023; Eulin Garrigue et al., 2017). Since 2014, this index referred to as Indice Diatomique des Antilles (IDA) has been routinely used to assess river water quality over the West Indies, particularly during the second WFD management plan (JORF, 2023) (an application to calculate the index is available on the website <https://see.eaufrance.fr>). In this study, we present the initial data acquisition context and the methodology developed for the elaboration of IDA. We then discuss its relevance in monitoring pressure gradients and make recommendations on the improvements that are needed today in light of its routine use.

Materials and methods

Sampling sites

The Martinique's hydrographic network is dense, with 70 rivers, 40 of them perennial. However, two major hydrographic units, or hydroecoregions, can be distinguished. Northern Martinique ("Pitons du Nord" hydroecoregion) is characterized by prominent mountains, including the Pelée Mountain and the "Pitons" ("Pitons du Carbet"). The rivers flowing from the Pelée Mountain have a relatively straight course due to steep slopes, while those flowing from

the Pitons show a more diversified morphology, with meanders in the downstream section. In both cases, short watersheds (mainly $< 15 \text{ km}^2$) and steep gradients (4% and more) generate torrential flows. The southern part of the island features gentler hills and fewer perennial rivers (“Mornes du Sud” hydroecoregion). The valleys widen due to low slopes that reach zero in the mangrove swamp zone. The clayey nature of the soils, combined with low rainfall, results in frequently low water levels. Guadeloupe is formed by two main islands separated by a marine inlet. The Eastern part, known as Grande Terre, is predominantly flat and characterized by limestone soils. Basse Terre, situated in the Western part, is a mountainous volcanic island featuring a north-to-south chain of volcanoes that defines its landscape. The highest peak is “La Soufrière,” an active volcano standing at 1467 m high, in the south. Basse-Terre is drained by more than fifty permanently flowing rivers, characterized by their short lengths, shallow depth, and small catchment areas (10 to 30 km^2). This hydrographic network is fed mainly by runoff, but is also supported by small aquifers. Its hydrological regime is torrential. Grande Terre in the east lacks perennial streams. Due to these contrasting, both territories are separated into two distinct hydroecoregions (HERs).

Martinique as well as Guadeloupe experiences a tropical climate with distinct dry (February to April) and wet (July to October) seasons. Sampling efforts were designed to best capture these climatic and geographical conditions and potential pollution sources that mainly originate from organic sources and pesticides related to the presence of crops, sugar factories, distilleries, slaughterhouses, and sewage treatment plants. Within the 2009–2013 period, 130 sites were sampled (70 from Martinique and 60 from Guadeloupe—Basse Terre—Fig. 1a and b, and Appendix 1), resulting in 607 samples with physicochemical and floristic data.

Physicochemical data

Environmental conditions in watercourses were estimated using 10 physicochemical variables: suspended matter (SM), biological oxygen demand (BOD5), nitrites (NO₂), nitrates (NO₃), orthophosphates (PO₄), ammonium (NH₄), Kjeldahl nitrogen (NKj), oxygen saturation (O₂.Sat), total phosphorus (Tot.P), and dissolved organic carbon (Org.C). All

analyses were carried out by six laboratories (departmental analysis laboratories—Pyrénées, Landes, Martinique, and Drôme; Pasteur Institute; and Lyon Carso Hygiene and Safety Laboratory), based on the same European standards (available on the European Committee for Standardization website: <https://standards.iteh.ai/catalog/tc/cen/fb2ac0f7-0811-458a-a4b3-b06e5456a865/cen-tc-230>).

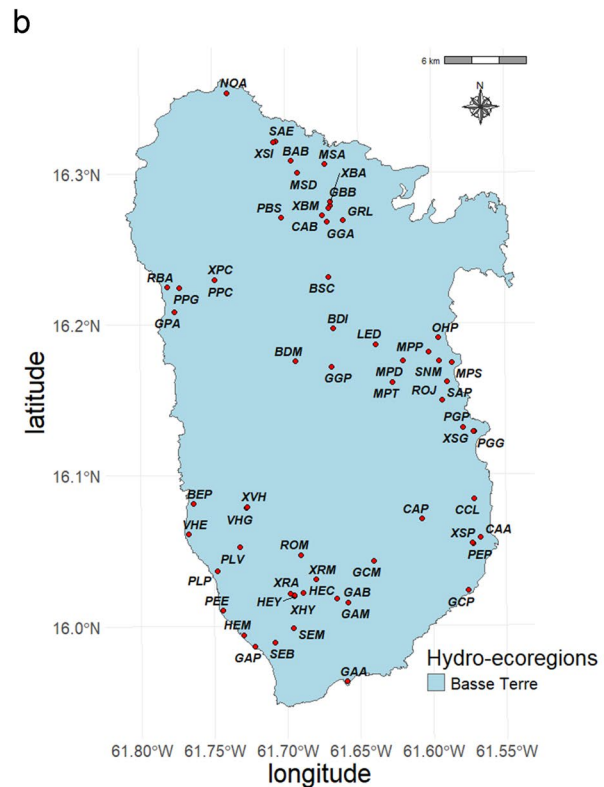
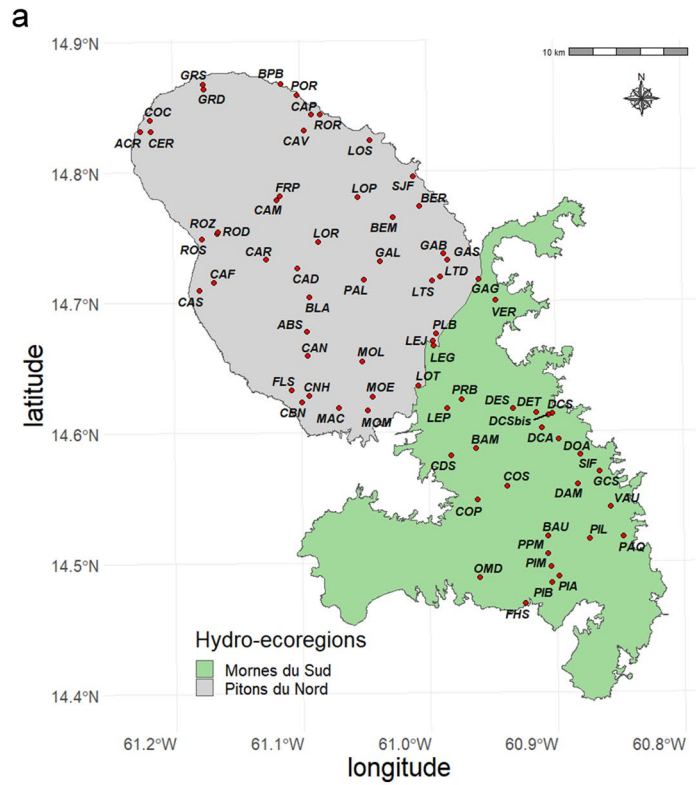
For further analysis, all abiotic variables that were not normally distributed were standardized (i.e., reduced and rescaled) using the Yeo-Johnson method as it takes into account null values (Riani et al., 2023; Yeo & Johnson, 2000). Potential autocorrelations among variables were checked using the Spearman method (De Winter et al., 2016).

Diatom data

Diatoms were sampled by Asconit Consultants, from hard substrates (pebbles and cobbles) under both dry and wet conditions according to the NF T90-354 protocol (AFNOR, 2016), in line with the European standards (EN 13946, CEN, 2003). Valves were identified at $1000\times$ magnification by examining permanent slides of cleaned diatom frustules, digested in boiling H₂O₂ (30%) and mounted in a high refractive index medium (Naphrax, Northern Biological Supplies Ltd., UK; RI = 1.74) (EN 13946, CEN, 2003). Four hundred valves per slide were counted and identified to obtain relative abundances for each taxon. Literature related to diatom taxonomy from the Caribbean islands is very sparse (but see Tudesque & Ector, 2002); some series must be cited in particular as they provide valuable drawings and micrographs to identify the diatom flora collected: *Iconographia Diatomologica*, *Diatoms of Europe*, *Sübwasserflora von Mitteleuropa*. Taxonomic homogenization was performed to avoid synonymy, as different appellations may coexist for the same taxa.

Thresholds were applied to retain only the taxa that provide relevant ecological information. First, taxa occurring in fewer than five samples were removed from the database. Among the remaining ones, only those showing at least one abundance data $> 2.5\%$ within all samples (Lavoie et al., 2009) were kept (hereafter referred to as “contributive taxa”). To capture the information provided by the less abundant taxa, relative abundances were log-transformed ($\log(x+1)$).

Fig. 1 **a** Map of sampling sites from Martinique with hydroecoregions (projection system WGS 84). **b** Map of sampling sites from the Basse Terre in Guadeloupe (projection system WGS 84)



Data analysis and index settlement

General approach

IDA calculation is based on the presence and abundance of contributive taxa (i.e., taxa for which an ecological profile was defined) in the sample considered. Five major steps are necessary. First, the environmental gradients driving sites and diatom communities were determined using multivariate analysis, following the concept of indirect gradient analysis explained by Ter Braak (2004). Two gradients were determined, one derived from principal component analysis (PCA) (Wold et al., 1987) applied to physicochemical data, and the other derived from canonical correspondence analysis (CCA) (Ter Braak & Verdonschot, 1995) applied to physicochemical and floristic data. The combination of both gradients led to settlement of a multimetric alteration gradient (MAG). Using this gradient, samples were distributed into distinct quality classes. Taxa ecological profiles were based on their presence probability along these classes, allowing us to determine an index score for all samples, based on floristic lists. All analyses were performed using R version 4.1.2 (2021–11-01) (R Core Team, 2021).

Multivariate analyses

A two-step analytical approach was used to gain comprehensive insights into the relationships between physicochemical variables and diatom data. As Martinique and Guadeloupe are part of the West Indies hydrosystem, merging data from both islands for analysis was prompted by the similarity in diatom communities. First, PCA was performed on the physicochemical data to provide a synthetic overview of environmental conditions at the study sites. CCA was subsequently performed to integrate both abiotic and floristic information and determine the ecological gradients that drive community composition. Analyses were based on log(x + 1) abundance data and centered and reduced physicochemical data. The statistical significance of the CCA was tested using ANOVA (Girden et al., 1992). Both analyses were performed using the “ade4” package (Chessel et al., 1995).

Multimetric alteration gradient (MAG)

Two gradients were first determined based on PCA and CCA results. The position of each sample in the gradient was estimated using the following equation:

$$\text{Gradient}_j = \sum_{i=1}^3 \text{inertia}_i * \text{projection}_{ji}$$

where *i* corresponds to the axis number and *j* to the sample.

Building a single gradient from PCA and CCA results enabled the integration of both physicochemical and biological information while enhancing the weight of environmental conditions. Both gradients were first normalized along a 0 to 1 axis, where samples closer to 0 indicated highly degraded environmental conditions.

Axis normalization was performed using the following formula:

$$\left(\frac{\text{maxA} - \text{minA}}{\text{maxVar} - \text{minVar}} \right) \times (\text{Var} - \text{minVar}) + \text{minA}$$

with maxA and minA corresponding to the maximum and minimum values of the desired range (in our case 0 to 1), maxVar and minVar to the maximum and minimum values of the vector to be scaled, i.e., the PCA or CCA gradient, and Var to the vector value to be scaled.

The multimetric alteration gradient was then written as the sum of the PCA and CCA gradient positions of all samples, leading to a single gradient scaled from 0 to 2.

Taxa ecological profiles After obtaining the MAG positions of all samples, a hierarchical classification (Husson et al., 2010) was performed to cluster them according to their scores. The relevance of the clusters obtained was tested using pairwise Wilcoxon tests (Wilcox, 2001) with a Bonferroni correction for multiple comparisons (Weisstein, 2004). Ecological profiles were then determined for each taxon, based on their presence probability across the different classes obtained.

$$P(\text{taxon}_{\text{class}}) = \frac{\text{OccTaxon}_{\text{class}} * \sum_{\text{class}=1}^5 \text{RelAbund}_{\text{taxon}}}{\text{NbSites}_{\text{class}} * A}$$

$$P(\text{taxon}_{\text{class}}) \in [0,1]$$

$$\text{with } A = \sum_{\text{class}=1}^5 \frac{\text{OccTaxon}_{\text{class}} * \sum_{\text{class}=1}^5 \text{RelAbund}_{\text{taxon}}}{\text{NbSites}_{\text{class}}}$$

where, for the class considered, $\text{OccTaxon}_{\text{class}}$ corresponds to the taxon occurrence in the class, $\text{RelAbund}_{\text{taxon}}$ to the relative abundance of the taxon in the class considered, and $\text{NbSites}_{\text{class}}$ to the number of sites in this class.

$$P(\text{Class1}) \geq 0.6 \ \& \ P(\text{Class1} + \text{Class2}) \geq 0.8 \ \& \ P(\text{Class4} + \text{Class5}) \leq 0.1$$

Taxa rather present in moderate quality classes were defined as “1–”:

$$P(\text{Class1} + \text{Class2}) \geq 0.55 \ \& \ P(\text{Class4} + \text{Class5}) \leq 0.175$$

All other taxa were not considered as “alert taxa” and were therefore classified as “1+.”

Index calculation Based on taxa ecological profiles and abundance data, the Indice Diatomique des Antilles (IDA) was computed as follows:

$$\begin{aligned} \text{IDA} = & \sum \text{Abund}_{\text{relative}}^{1+} * \left(\frac{\text{Nbsp}^{1+}}{\text{SR}} \right) \\ & - \left(1 * \left(\sum \text{Abund}_{\text{relative}}^{1-} * \left(\frac{\text{Nbsp}^{1-}}{\text{SR}} \right) \right) \right) \\ & - \left(3 * \left(\sum \text{Abund}_{\text{relative}}^{2-} * \left(\frac{\text{Nbsp}^{2-}}{\text{SR}} \right) \right) \right) \end{aligned}$$

where SR corresponds to the specific richness of all contributive taxa, Nbsp^+ to the number of taxa classified as “1+,” Nbsp^{1-} to the number of taxa classified as “1–,” and Nbsp^{2-} to the number of taxa classified as “2–.” Abund^+ corresponds to the relative abundance of “1+” taxa, Abund^{1-} to the relative abundance of “1–” taxa, and Abund^{2-} corresponds to the relative abundance of “2–” taxa.

A greater weight (–3) was assigned to taxa present in highly impacted environments. The more “2–” taxa in the sample, the lower the IDA score. The worst-case scenario for alteration in a survey thus involves only “2–” taxa, each with an alteration coefficient of –3, resulting in a final score of –300.

Three types of ecological profiles were determined: “2–,” “1–,” and “1+.”

Taxa with high presence probabilities in bad quality classes were called “alert taxa” and were defined as “2–” or “1–” depending on these probabilities (if we consider that the hierarchical analysis resulted in five classes):

Taxa with the highest presence probabilities in the worst quality classes were defined as “2–”:

Scores could initially range from +100 (optimal conditions) to –300 (worst conditions), forming a 400-unit scale. Although the best conditions can be found in some sites, the worst theoretical conditions of only “2–” taxa never occur in reality. Even in severely altered areas, watercourses still carry positive (+) and negative (–) taxa, preventing the score from dropping to –300. In practice, even in the most polluted watercourses in the Antilles, the lowest recorded score is –148, observed downstream of a highly polluting STEP discharge, and it is unlikely that a lower score will ever be encountered. For this reason, we decided to set the lowest possible IDA score to –150. Then, the scores were normalized to a [0]–[+20] scale as follows:

$$\text{IDA}_{/20} = \frac{\text{IDA} - 150 (-3 * 100)}{100 (\text{IDA}) - 150 (-3 * 100)} * 20$$

where –150 represents the lowest possible value of IDA, 100 is the highest, and –3 is the weight attributed to “2–” taxa.

Index validation

We used a set of new samples collected from Martinique and Guadeloupe between 2014 and 2022 for index validation. In total, 457 new samples, all characterized by complete physicochemical and biological data, were used as a validation matrix. First, we projected the new data onto the three PCA and CCA dimensions to calculate the new MAG scores. To do so, biological and physicochemical matrices underwent several modifications.

- Only taxa from the new community matrix that were present in the initial one were considered, and then (log + 1) transformed as previously;
- For a few samples, not all physicochemical variable values were recorded. To make sure we had a complete set to work on, we decided to predict those missing values using the “MICE” package in R (R Development Core Team, 2021).

Samples’ positions on the PCA were obtained by displaying the new physicochemical data on the different dimensions using the “suprow” function from the “ade4” package (Chessel et al., 1995). Samples’ positions on the CCA were obtained for the new community matrix using weighted constrained averages of the initial species scores (WA scores) using the “vegan” package (predict.cca function, Dixon, 2003). Finally, we calculated and normalized the new MAG values and performed a Spearman correlation test (De Winter et al., 2016) between new IDA scores (computed from new data abundances) and MAG values.

In the second step, we performed a multiple linear regression model to investigate the potential relationships between IDA scores and physicochemical variables using the new dataset. The best model was selected based on Akaike’s information criterion (AIC) (Akaike, 1974), performed with the “stepAIC” function from the R package MASS (Ripley et al.,

2013). We then tested the correlation between IDA scores predicted by the selected model and the real scores using the Spearman method.

Results

Biological and physicochemical data

The 607 biological surveys carried out between 2009 and 2013 have made it possible to identify and inventory 512 different taxa that can now be recognized and counted, among which 60% have been described as new.

Few taxa were abundant (e.g., *Achnanthydium minutissimum*, *Mayamaea perimitis*, *Nitzschia tri-punctata*, *Nitzschia gregaria*), whereas 435 were present in less than 10% of the samples. After implementing the criteria for selecting the most contributive ones, 178 taxa were included in the dataset (Appendix 2).

Concerning physicochemical data (Table 1), the value distribution ranges for oxygen saturation, suspended matter, organic carbon, and BDO5 were particularly wide (and to a lower extent for NH₄, NO₃, and KjN). Some sampling sites were located directly at the effluent discharge points of wastewater treatment plants (BAB, GBB, HEY, OHP, PGG, PEP,

Table 1 Physicochemical data available for analyses

Variable	Units	Minimum	25th Percentile	Median	75th percentile	Maximum	Mean	Standard deviation
Oxygen saturation (O ₂ Sat)	%	2.190	91.000	97.500	101.400	157.5	92.278	19.507
Suspended matter (SM)	mg/L	0.330	2.600	8.200	24.500	289.0	18.773	28.382
Total phosphorus (tot.P)	mg/L	0.007	0.017	0.040	0.140	7.3	0.143	0.397
Orthophosphate (PO ₄)	mg (PO ₄)/L	0.000	0.030	0.050	0.125	16.0	0.229	0.887
Organic carbon (Org.C)	mg/L	0.067	0.800	1.220	2.055	200.0	2.689	12.148
Biological oxygen demand (BDO5)	mg O ₂ /L	0.170	0.170	0.700	1.045	410.0	2.495	22.875
Kjeldahl nitrogen (KjN)	mg N/L	0.130	0.167	0.333	0.500	61.1	0.876	3.331
Ammonium (NH ₄)	mg (NH ₄)+/L	0.008	0.017	0.020	0.030	67.0	0.607	3.856
Nitrites (NO ₂)	mg (NO ₂)-/L	0.007	0.008	0.010	0.020	12.0	0.084	0.569
Nitrates (NO ₃)	mg (NO ₃)-/L	0.030	0.330	0.620	2.900	25.5	2.166	3.322

XHY, XSG, and XSP for Guadeloupe and CAS, CDS, DCA, FHS, FLS, GCS, and LTS for Martinique), leading to high nutrient and organic matter loads. The maximum autocorrelation between variables was 0.627, and concerned NH_4 and NO_2 . We considered that this value was not sufficiently high to remove any variable from the ten listed above.

Multivariate analyses

Only the first three axes of PCA (Fig. 2a and b) and CCA (Fig. 3) analyses were considered, as the amount of information carried by other dimensions was negligible (less than 10%).

Concerning PCA, axis 1 explained nearly 43% of the total variance and axes 2 and 3 respectively 14.9% and 9.9% (Fig. 2). Oxygen saturation, primarily driven by the third axis (42%), appeared opposed to the other variables. Axes 1 and 2 captured most other variable variances except NO_3 , rather linked to the second and third axes (Table 2).

Concerning the CCA, axis 1 carries the most important part of the variance, i.e., 40.3%, and axes 2 and 3 respectively 17.6% and 11.2% (Fig. 3). The total constrained inertia was 7.2, in line with the classical values obtained when working on diatom flora (Vyverman et al., 2007). The ANOVA p -value was <0.001 , indicating a significant effect of the environmental conditions on the communities. Again, oxygen saturation was opposed to all other variables. Diatom communities appeared significantly driven by variables linked to eutrophication and organic pollution. The importance of O_2 .Sat in the spatial distribution of the data reflects the geographical influence of hydroecoregions. Samples from Pitons du Nord for example, characterized by prominent mountains and fast-flowing streams, present high levels of O_2 .Sat and are consequently grouped in the right part of axis 1 on the CCA plots.

Ecological profiles settlement

The hierarchical classification of the MAG scores resulted in five distinct water quality classes (Table 3).

Forty-four percent of the samples were assigned to the good or very good quality classes, 30% to the medium quality class, and 26% to the bad and very bad quality classes. Environmental conditions in each quality class are given in Table 4. The statistical

Wilcoxon pairwise comparison results between classes are available in Appendix 3.

The a priori partition into five classes appeared relevant, with each class being significantly different from the others for at least one variable (see Appendix 3). Based on these results, ecological profiles were calculated for each taxa, which were subsequently classified into alert taxa (“2–” or “1–”) and “1+” taxa (Appendix 2). Finally, 131 taxa were associated with a “1+” profile, 25 with a “1–” profile, and 22 with a “2–” profile. Examples are given in Fig. 4: ADEG (*Achnantheidium exiguum*) is specific to very bad quality classes (“2–” profile) while CMLF (*Craticula molestiformis*) exhibits greater tolerance for classes 1 and 3 (“–1” profile), and ADSH (*Achnantheidium subhudsonis*) thrives in good conditions (“+1” profile).

Index calculation

Globally, most IDA scores ranged from 15/20 to 20/20 and indicated good to very good water quality conditions, at least for the variables taken into account in the MAG; a few samples were characterized by low scores (Fig. 5). The average score across all the samples was 17.81/20, with a low standard deviation (2.93). No scores below 15–20 were found at sites above 200 m high.

Consequently, global IDA scores were greater in the mountainous HER (Basse Terre in Guadeloupe and Pitons du Nord in Martinique) than in the lowlands (Mornes du Sud in Martinique) (Fig. 6). Median scores were significantly different according to the HER in Martinique (p -value $<2.2 \times 10^{-16}$; Wilcoxon test). Samples with the lowest scores were all located downstream of wastewater treatment stations or slaughterhouses.

Index validation

New MAG computation

Strong positive and significant correlations between MAG and IDA scores were obtained for both the 2009–2013 (correlation coefficient = 0.74; p -value $<2.2 \times 10^{-16}$) and the 2014–2022 (correlation coefficient = 0.75; p -value $<2.2 \times 10^{-16}$) datasets (see Fig. 7).

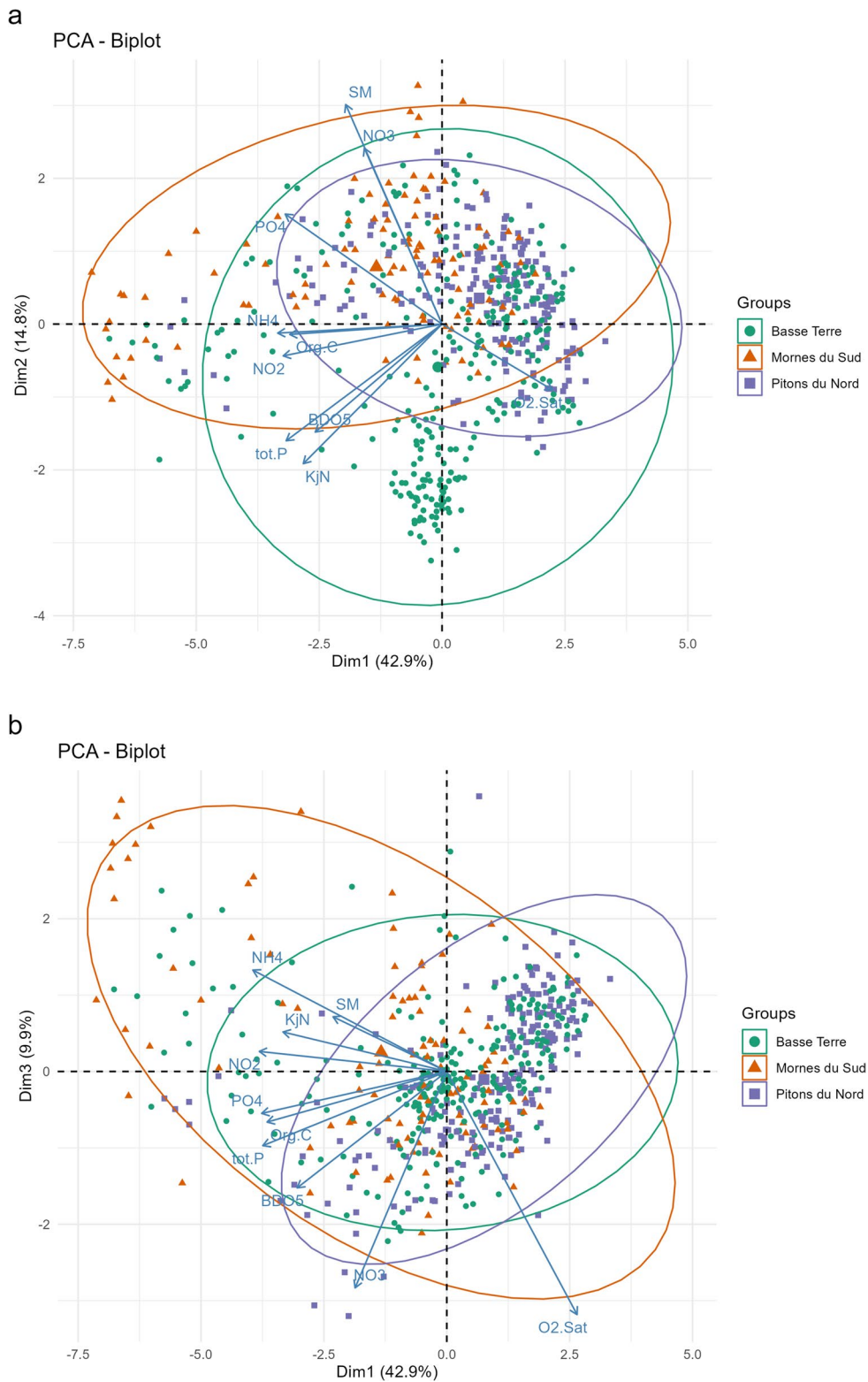


Fig. 2 Correlation plots of the first three PCA components: **(a)** axes 1 and 2, **(b)** axes 1 and 3

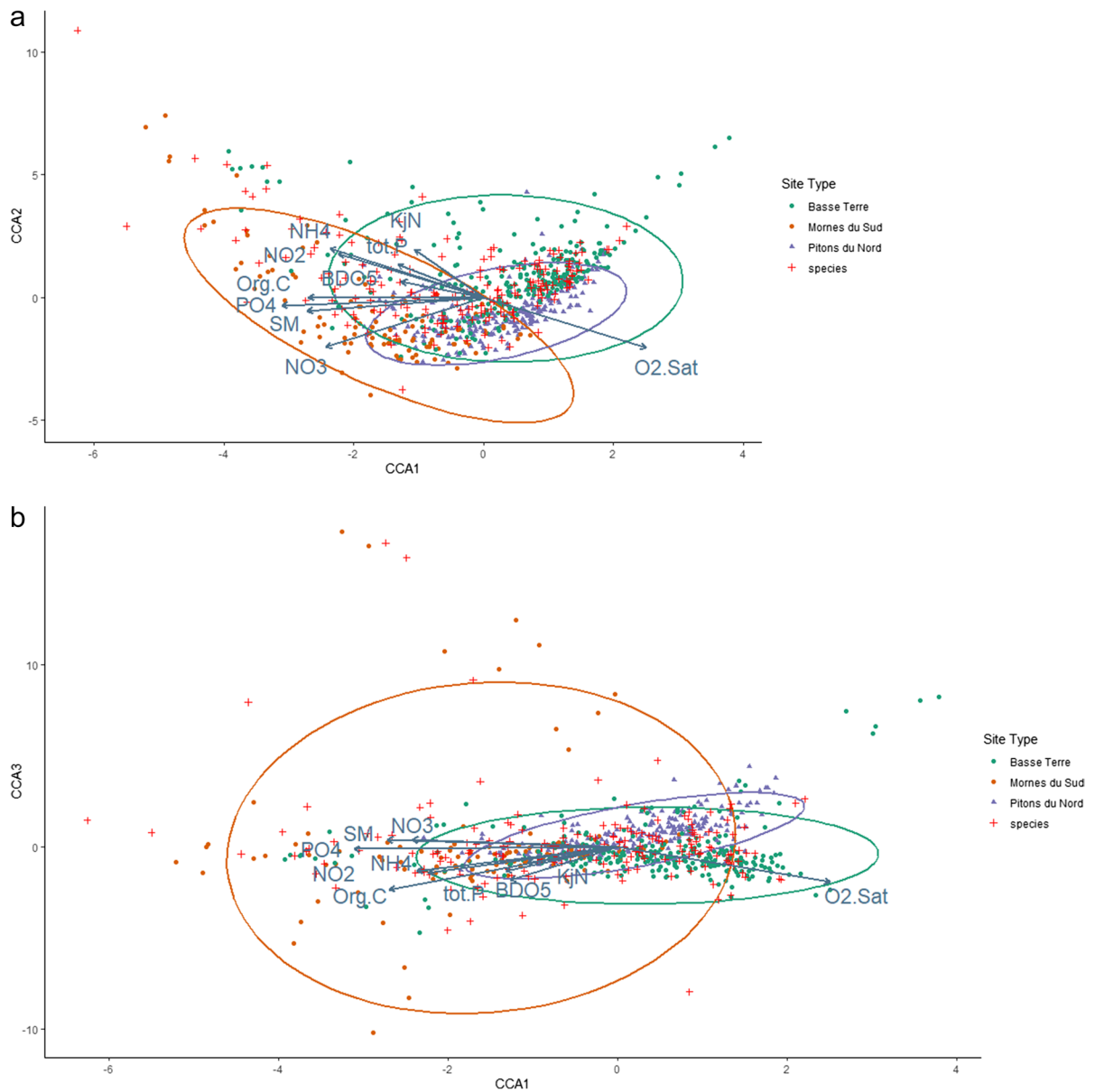


Fig. 3 Ordination plots of the three first CCA axes using WA scores (taxa scores): **(a)** axes 1 and 2, **(b)** axes 1 and 3

Pressure-impact approach

The best-selected model, with an AIC of 139.51, showed significant negative relationships between

new IDA scores and suspended matter (SM), nitrates (NO₃), ammonium (NH₄), and dissolved organic carbon (Org.C) values ($R^2=0.51$, p -value $< 2.2 \times 10^{-16}$). Based on this model, predicted IDA scores (from SM,

Table 2 Variable contributions on PCA axis

Parameter	Axis 1	Axis 2	Axis 3
Org.C	12.39	0.12	1.55
BDO5	8.63	8.00	9.62
SM	4.87	34.05	2.13
NH ₄	14.47	0.09	7.27
KjN	10.36	13.14	0.72
NO ₂	13.49	0.84	0.39
NO ₃	3.13	23.10	30.49
PO ₄	13.05	9.24	1.29
tot.P	13.07	8.82	4.53
O ₂ -Sat	6.53	2.58	42.02

NO₃, NH₄, and C.org) were well correlated with the observed IDA scores (Spearman correlation coefficient=0.48, *p*-value < 2.2 × 10⁻¹⁶).

Discussion

European overseas regions such as the Caribbean islands have been widely overlooked until recently because of their particular bioclimatic and geomorphological conditions (Dedieu et al., 2014). This paper introduces the West Indies Diatom Index (IDA) which meets WFD requirements, addressing the region’s need for a suitable index to monitor aquatic ecosystem health.

Through multivariate analyses, we identified the key abiotic factors influencing diatom communities in Martinique and Guadeloupe. Contributive taxa were assigned to a specific ecological profile, based on their presence probability along a pressure gradient. Three types of profiles were determined: “2 –” for most tolerant taxa occurring in most altered conditions, “1 –”, and “1 +” for sensitive taxa occurring in good water quality sites.

Utilizing taxon abundance data and ecological profiles from the samples, we calculated the West Indies Diatom Index and verified its effectiveness using data from 2014 to 2022 as a validation dataset.

Index accuracy

Results revealed a globally good water quality for most water bodies (about 88% of the samples). A posteriori validation of this index demonstrated however its ability to reveal water quality loss due to an overload of nutrients or organic matter of anthropogenic origin. In freshwater biomonitoring, diatom-based indices are commonly used to capture species and community responses to environmental conditions, particularly eutrophication and organic pollution (Passy & Bode, 2004). Changes in diatom communities have been proven to be strongly linked to nutrient loads, as nutrient enrichment benefits the colonization of water bodies by generalist taxa and poor competitors for resources (Leboucher et al., 2019). As such, generalist taxa are found worldwide where eutrophication occurs and contribute as key tolerant species to any diatom-based index, in continents or islands. Thus, among taxa classified as “2 –” or “1 –” in IDA, some present a typical profile of tolerant species according to the diatom-based index used in continental France (BDI, Biological Diatom Index, Coste et al., 2009) such as *Nitzschia amphibia* (Geitler, 1969), *Sellaphora seminulum* (Wetzel et al., 2015), or *Eolimna subminuscula* (now *Craticula subminuscula*, Wetzel et al., 2015) among others.

At the same time, the IDA is able to capture local specificities that indices such as the BDI cannot, firstly concerning organic matter, which can have two different origins in the rivers of Martinique and Guadeloupe: anthropogenic and natural. In fact, rivers are often rich in plant litter or fruit,

Table 3 Water quality classes estimated from MAG scores

Class	1	2	3	4	5
Quality level	Very bad	Bad	Medium	Good	Very good
MAG score	(0.182–0.611]	(0.611–0.903]	(0.903–1.11]	(1.11–1.3]	(1.3–1.94]
Number of samples	62	101	183	159	102

Table 4 Environmental conditions in the 5 quality classes (minimum, maximum; median)

Group	O ₂ Sat	SM	tot.P	PO ₄	Org.C	BDO5	KjN	NH ₄	NO ₂	NO ₃
1	[2.19, 157.5]; 61.75	[5.2, 184]; 30.5	[0.04, 7.3]; 0.305	[0.06, 16]; 0.48	[1.4, 200]; 3.9	[0.5, 410]; 1.7	[0.167, 61.1]; 1.85	[0.017, 67]; 0.77	[0.01, 12]; 0.17	[0.033, 25.5]; 1.85
2	[24, 124.5]; 96	[0.67, 246.8]; 20	[0.007, 1.79]; 0.11	[0.005, 1.36]; 0.17	[0.6, 17.17]; 2.05	[0.17, 19]; 0.9	[0.13, 3]; 0.333	[0.01, 3.6]; 0.02	[0.007, 1]; 0.02	[0.1, 12.9]; 3
3	[47.8, 142.3]; 98.5	[0.67, 289]; 5.4	[0.007, 1.63]; 0.06	[0, 0.27]; 0.03	[0.4, 13.73]; 1.4	[0.17, 7]; 0.9	[0.13, 1.63]; 0.333	[0.008, 0.96]; 0.02	[0.007, 1.2]; 0.017	[0.03, 14.3]; 0.77
4	[31, 127]; 98.5	[0.33, 53]; 5	[0.007, 0.62]; 0.017	[0, 1.29]; 0.03	[0.1, 5.165]; 0.9	[0.17, 4.2]; 0.5	[0.13, 0.92]; 0.22	[0.008, 0.14]; 0.017	[0.007, 0.08]; 0.01	[0.03, 14.3]; 0.41
5	[8.06, 115.8]; 98.05	[0.33, 52]; 6.05	[0.007, 0.06]; 0.01	[0, 0.1]; 0.02	[0.067, 2.56]; 0.6	[0.17, 1.97]; 0.17	[0.13, 0.5]; 0.17	[0.01, 0.19]; 0.02	[0.007, 0.14]; 0.01	[0.03, 1.8]; 0.33

which leads to significant levels of organic matter and, consequently, to a high abundance of taxa such as *Fistulifera saprofila* (FSAP). This species is considered by the BDI to be one of the indicator species for poor water quality and its high abundance leads to very low index values. IDA, however, does not classify this species as an alert taxon because FSAP is often associated with natural organic matter enrichment. This avoids inappropriate downgrading of very good quality sites. Secondly, given the high number of endemic species in the Caribbean islands, assessing the ecological status of rivers in Martinique and Guadeloupe using BDI is irrelevant because too few taxa are included in the calculation of the score. In fact, the BDI scores for the samples in our dataset were based on an average of only 48% (min = 5.5, max = 100, median = 48) of the taxa from the floristic lists against 99% for IDA (min = 60, max = 100, median = 100).

The main challenge to settle IDA arose from the very particular climate and geomorphological conditions of the West Indies, characterized by a lack of intermediate situations along abiotic gradients, most of which have a near-binary distribution between low and maximal alteration (Table 1). For example, IDA score differences between the two HERs from Martinique are directly linked to their hydrodynamic natures, raising a subsequent proposition of distinct good ecological status thresholds (JORF, 2023). Because most rivers are torrential systems with strong currents and steep slopes, pollution is directly driven downstream. If the majority of existing bioindicators are calculated as an abundance-weighted average of every taxon ecological profile from a sample, this method is far from optimal for datasets showing these specific environmental conditions. In such cases, identification of alert taxa seems more appropriate than considering diatom communities as a whole (Carayon et al., 2020). The use of alert taxa, to which the index formula also gives special weight, increases the alteration signal, making it easier to detect. All samples from sites downstream of sewage treatment plants, farms, or distilleries had low IDA scores. This makes sense, given that subsequent index validations with new data collected between 2014 and 2022 confirmed the significant relationship between anthropogenic variables that contribute to the MAG (in particular suspended matter, nitrates, ammonium, and dissolved organic carbon) and IDA scores.

Fig. 4 Examples of ecological profiles (i.e., presence probability of the taxon considered among the five quality classes). ADEG, *Achnanthydium exiguum* (now *Gogorevia exilis* (Kützing), Kulikovskiy et al., 2020); ADSh, *Achnanthydium subhudsonis* (Hustedt) (Kobayasi, 2006); CMLF, *Craticula molestiformis* (Hustedt) (Mayama, 1999)

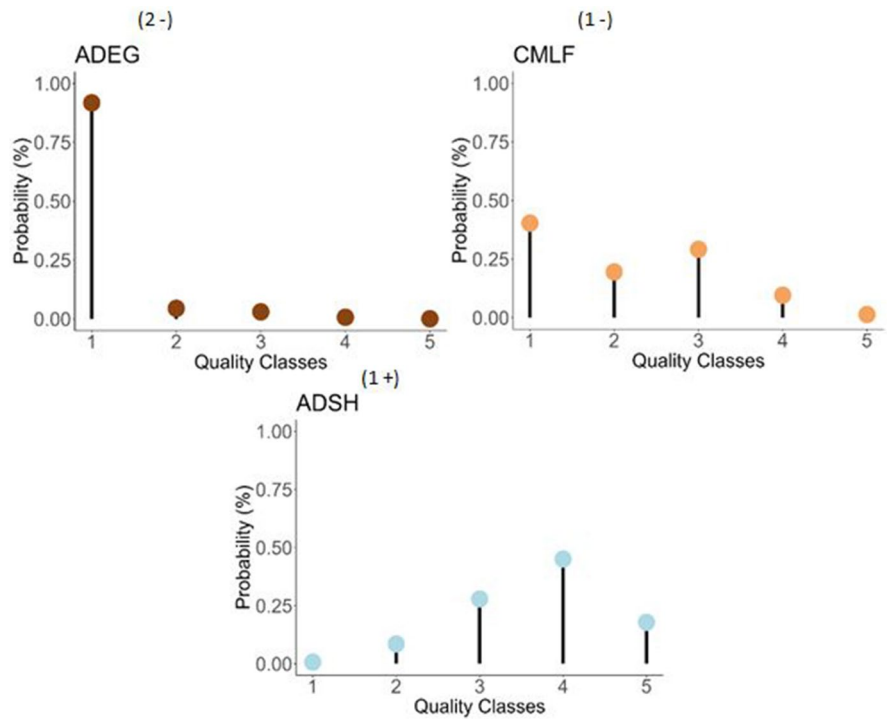


Fig. 5 Two-axis histogram showing IDA score' frequency and altitude

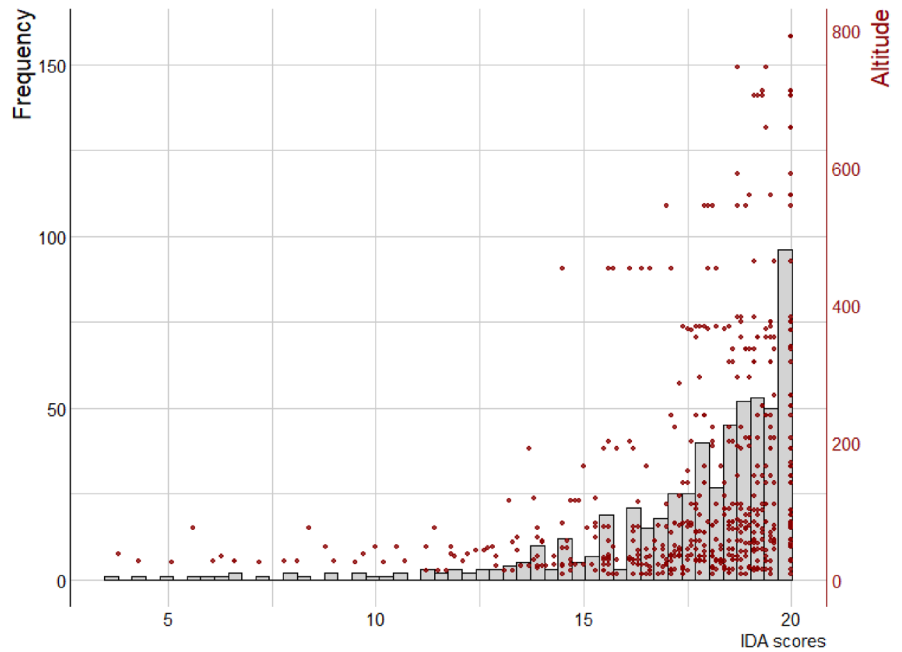
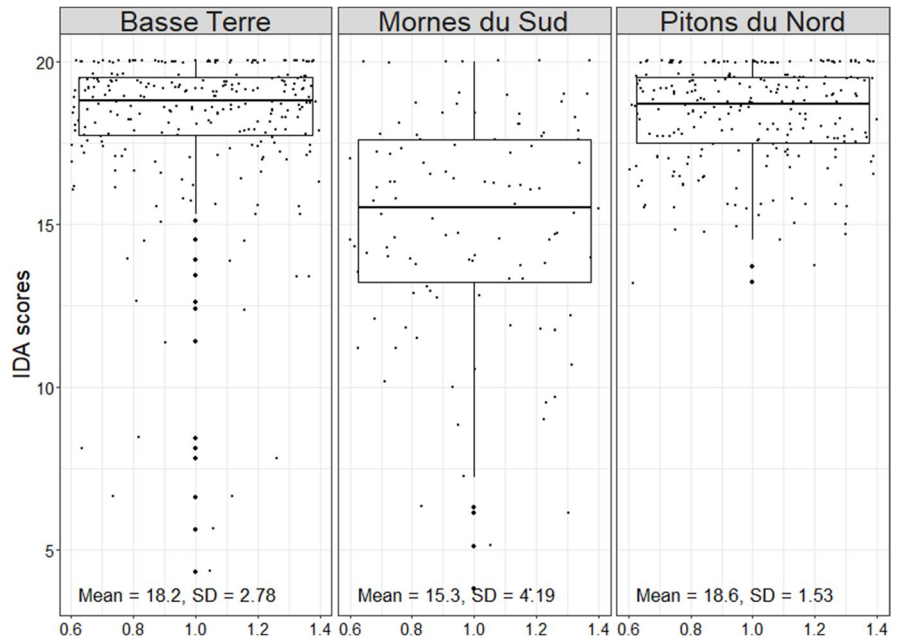


Fig. 6 Boxplots of IDA scores in Guadeloupe (Basse Terre) and Martinique (Mornes du Sud, Pitons du Nord) hydroecoregions (HER)



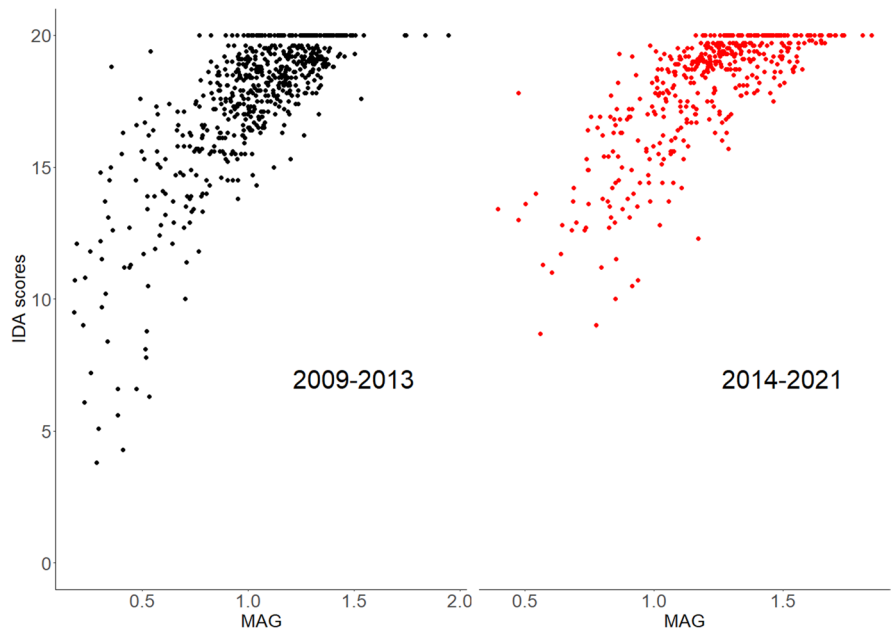
Future developments

A need for new data...

It is evident that because of the lack of data in the initial dataset used to settle IDA, taxa profiles' over- or underestimation may have occurred,

particularly for taxa that were recorded less than 10 times in our dataset. Furthermore, floristic and physicochemical samples were not sufficiently frequent in some years, and were sometimes not temporally synchronized. New data that will be collected in the coming years must be used to strengthen the robustness of diatom species profiles

Fig. 7 Relationships between IDA and MAG scores for the 2009–2013 and 2014–2022 datasets



and consequently, to facilitate the detection of long-term trends and changes in aquatic ecosystems in the West Indies.

... and complementary approaches

We believe that the particular geomorphology of Martinique and Guadeloupe makes it difficult to identify relationships between abiotic variables that are routinely measured and diatom community composition. In this context, how can the assessment of the river ecological status be facilitated?

First, microhabitats should be well-documented. The torrential nature of rivers leads to a mosaic of local conditions where contrasting current speed, light, and temperature can significantly impact diatom community composition (Jamoneau et al., 2022). Investigation of these particular microhabitats, together with a thorough description of the geological substrate and the riparian vegetation, could help improve our knowledge of the relationships between abiotic conditions and diatom species on islands, and design dedicated sampling protocols.

Second, the Martinique and Guadeloupe rivers flow directly into the surrounding ocean, making coastal ecosystems natural reservoirs of all types of pollution generated upstream on the islands. These coastal zones are monitored by the WFD (based on biological elements such as macroinvertebrates, physicochemical data, and specific pollutants including chlordecone). Therefore, it is particularly relevant in such an island context to take a close look at these assessments, as they shed light on the continental river status. In particular, Desrosiers et al. (2013) mentioned that coastal benthic diatoms could consist in a powerful water quality assessment tool, as they might be directly and strongly affected by continental water quality changes.

Conclusion

IDA fulfills the WFD requirements of considering the abundance and sensitivity of taxa to pollution for the evaluation of river ecological status. Considering that the fast-flowing nature of the rivers makes any index based on macrophytes inapplicable, IDA is a key element for aquatic system monitoring in the West

Indies, complementary to the macroinvertebrate-based index (Touron-Poncet et al., 2014).

Nevertheless, further development is required to enhance IDA's efficiency. Prior studies must include better taxonomic knowledge of diatoms, an improvement in the periodicity and synchronicity of sampling surveys, larger datasets, and a deeper investigation of microhabitats. These improvements will undoubtedly strengthen the ecological profiles of taxa and the robustness of ecological status assessments derived from IDA.

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Data availability Data that support the findings of this study have been deposited in the "recherche.data.gouv" website:

<https://doi.org/https://doi.org/10.57745/AEGOGN> (physicochemical data)

<https://doi.org/https://doi.org/10.57745/WSUMAV> (biological data)

Declarations

Competing interests The authors declare no competing interests.

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