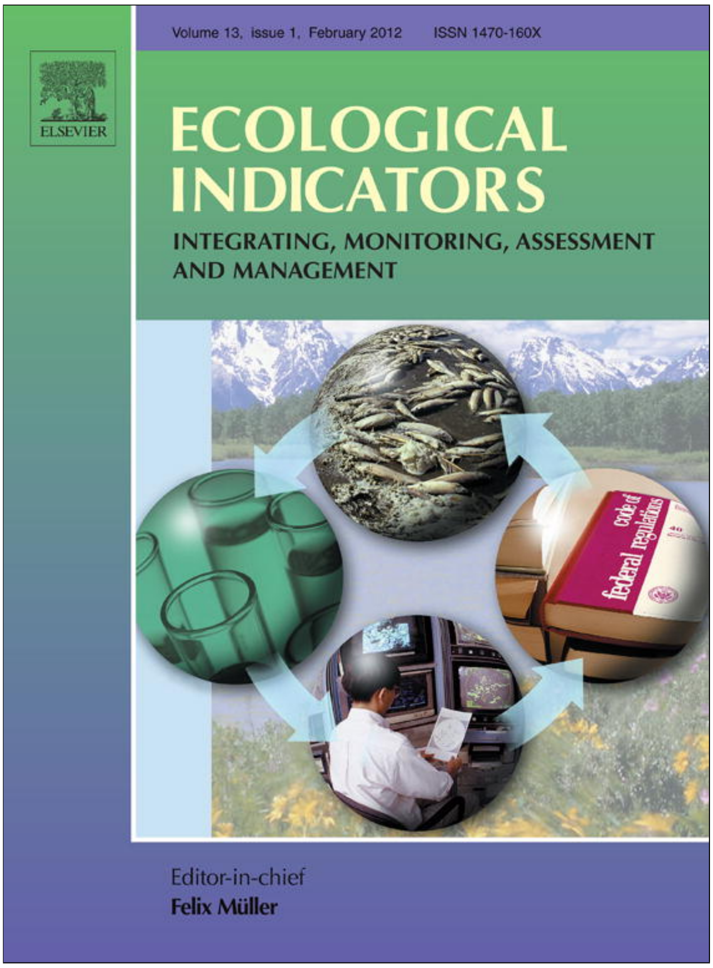
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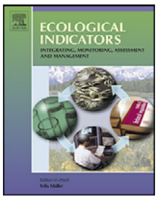

Short communication

Applicability of the Pampean Diatom Index (PDI) to streams around São Carlos-SP, Brazil

Taurai Bere*, José Galizia Tundisi

Instituto Internacional de Ecologia, Rua Bento Carlos, 750, Centro, São Carlos, São Paulo, CEP 13560-660, Brazil

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ABSTRACT

The objective of the current study was to assess the applicability of the Pampean Diatom Index (the PDI) to natural communities other than epipelic diatom communities as well as those growing on artificial substrates in Monjolinho River and its tributaries, São Carlos-SP, Brazil. Benthic diatoms and water quality sampling was done at 10 sites during summer base flow period (2008 and 2009). The PDI scores were calculated based on epilithic, epiphytic, epipsammic and epipelic diatom communities as well as those growing on bricks and glass substrates. Pearson correlation was used to determine the relationship between the PDI scores from different substrates sampled and measured physical and chemical water quality data. Two-way ANOVA was used to compare these correlation values among substrates. The PDI scores based on all the substrates showed significant correlations with physical and chemical variables. Insignificant differences in the PDI scores based on different natural substrates were recorded, with all substrates classifying the sites into roughly the same categories. In the light of these results, the PDI can be applied to communities other than epipelic, and is applicable to the study area. The choice of substrate sampled may not affect accuracy of the PDI-based water quality assessment.

1. Introduction

Diatom-based indices are increasingly becoming important tools for assessment of ecological conditions in lotic systems. Wide geographic distribution and well-studied ecology of most diatom species are cited as major advantages of using diatoms as indicator organisms (Round, 1991, 1993; McCormick and Cairns, 1994; Prygiel et al., 1999; Potapova and Charles, 2005; Lowe and Pan 1996; Taylor et al., 2007). These assumptions imply that diatom-based water quality assessment tools should have universal applicability across geographic areas and environments (Round, 1991; Potapova and Charles, 2005). For this reason, due to lack of information on ecological preferences and tolerances of diatoms in some regions, indices developed in other regions are often used. Taylor et al. (2007) recommended that diatom indices developed in other regions could be used for gaining support and recognition for diatom-based approaches to water quality monitoring allowing for sample and data collection, which can then be used later in the formulation of a unique diatom index. Strict testing of these indices developed in other regions is required to ensure that diatom index scores give a realistic reflection of the specific type of environmental pollution being tested in the study region.

The use of diatoms as indicators of water quality changes has relatively few precedents in South America compared to North America and Europe. Gomez and Licursi (2001) published a regional water quality evaluation index for rivers and streams in the Pampas of Argentina, the Pampean Diatom Index (the PDI), based on the sensitivity of the epipelic diatom assemblages to the integrated effects of organic enrichment and eutrophication. This index is based on epipelic instead of the traditionally favoured epilithic diatom communities due to absence of stones in the region studied, as was the case at some of the sites in this study. We have demonstrated that results of diatom-based multivariate water quality assessment based on different substrates may be interchangeable (Bere and Tundisi, 2011). This is also supported by studies in which values of trophic and saprobic diatom indices did not differ whether they were derived from epilithon, epipelon or epiphyton (Rott et al., 1998; Kitner and Poulí-Čková, 2003) as well as other studies such as Potapova and Charles (2005). Thus, the objective of the current study was to assess the applicability of the PDI to natural communities other than epipelic diatom communities as well as those growing on artificial substrates in Monjolinho River and its tributaries, São Carlos-SP, Brazil.

2. Materials and methods

2.1. Study area

The study area is shown in Fig. 1. Headwaters of Monjolinho and the tributaries studied fall within mainly agricultural area. From

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* Corresponding author. Tel.: +55 16 3362 5400; fax: +55 16 3362 5400.
E-mail addresses: taubere@yahoo.com (T. Bere), tundisi@iie.com.br (J.G. Tundisi).
URL: http://www.iie.com.br (T. Bere).

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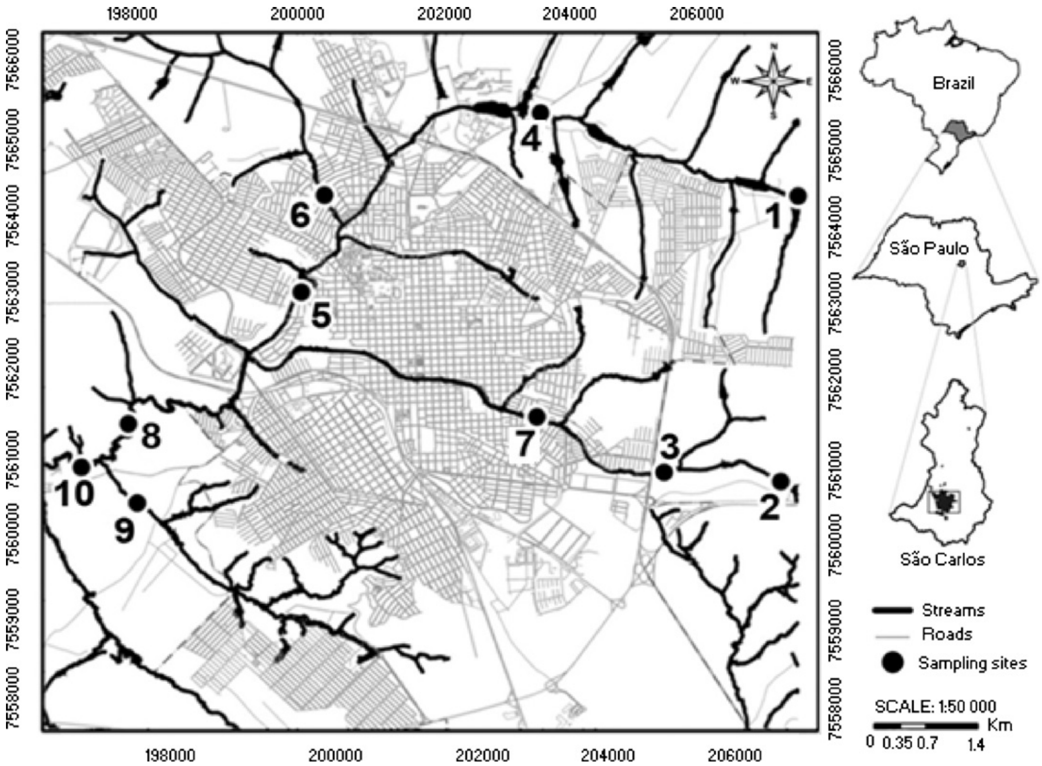

Fig. 1. The location of the sampling sites in the study area.

agricultural area, the streams pass through urban area of the city of São Carlos, which covers a total area of 1143.9 km^2. The expansion of the city does not meet the technical standards that go with it in terms of sewage treatment, collection of garbage, urban drainage and so on. Streams in the study area, therefore, receive untreated or semi-treated effluent from various domestic and industrial sources as well as other diffuse sources as they pass through the city. This disorderly growth of the city results in stream health deterioration, loss of the remaining primary vegetation organic pollution and eutrophication among other problems.

Ten sites were established along the Monjolinho river and its tributaries: four sites (1, 2, 3 and 4) in the relatively less impacted agricultural and forested headwaters to act as reference sites; three sites (5, 6 and 7) in the moderately polluted urban area; and three sites (8, 9 and 10) in highly polluted downstream area after the urban area (Fig. 1). The rational for choosing the sampling sites was to obtain a pollution gradient of all the stream systems from relatively unpolluted agricultural headwaters to highly polluted urban downstream sites. Substrate assessment, diatom and water quality sampling were done during dry seasons (autumn and winter) when flow was stable. Four samplings were carried out, two in September and October 2008 and two in May and June 2009.

2.2. Data collection

Environmental variables recorded at the sampling sites are shown in Table 1. Their collection and analysis is outlined in Bere and Tundisi (2011). At each site, epilithic, epiphytic, epipsammic and epipelic diatom samples were collected separately as outlined in Bere and Tundisi (2011). At each site, two bricks and four rough glass slides mounted on a rack (artificial substrates) were immersed in the water column, parallel to the current at a depth of 20–30 cm below the surface and left for four weeks. Detailed description of the way these artificial substrates were handled and sampled is found in Bere and Tundisi (2011). In the laboratory, sub-samples of the diatom suspensions were cleaned of organic material mounted and diatom valves identified and counted as outlined in Bere and Tundisi (2011).

2.3. Data analysis

Diatom assemblages and their relationships with measured environmental variables are discussed in Bere and Tundisi (2011). The PDI was calculated following Gomez and Licursi (2001). The PDI values range from 0 to 4 as follows: 0–0.5 (very good), >0.5–1.5 (good), >1.5–2 (acceptable); >2–3 = bad and >3–4 (very bad) water quality. After testing for homogeneity of variances (Levene's test, $p \leq 0.05$) and normality of distribution (Shapiro–Wilk test, $p \leq 0.05$) and transforming where necessary Bere and Tundisi (2011), two-way ANOVA was used to compare means of environmental variables among the three sites categories (Section 2.1). Pearson correlation was used to determine the relationship between the PDI scores based on different substrates sampled and measured concurrent physical and chemical water quality data. One-way ANOVA was used to compare the PDI scores among substrates. Pearson correlation, ANOVA, Levene's test and Shapiro–Wilk were performed using PAlaeontological STatistics (PAST) software version 1.95 (Hammer et al., 2009).

3. Results

3.1. Physical and chemical variables

The pH increased slightly down the agricultural to urban gradient being slightly acidic at upstream sites and slightly alkaline/neutral at downstream sites. However, the difference in pH among the three site categories (Section 2.1) was not statistically significant (ANOVA, $p > 0.05$). Temperature increased downstream, but as in the case of pH, the increase was not significant (ANOVA, $p > 0.05$). On the other hand, conductivity, BOD$_5$, COD, TDS, tur-

Table 1
The mean ($n = 4$) values of physical and chemical variables measured at 10 sites during four sampling periods.

	Site									
	1	2	3	4	5	6	7	8	9	10
Temperature (°C)	18.3	20.9	20.6	21.2	21.2	20.39	24	24.8	23	21.3
Altitude (m)	761	837	831	794	745	761	774	724	630	627
Canopy cover (%)	80	95	60	50	4	45	20	20	50	5
BOD_5 ($mg\,L^{-1}$)	0.9	1	2.6	6.9	1.2	7.2	1.6	19.5	24.5	26.2
DO ($mg\,L^{-1}$)	7.3	8.2	7.6	6.9	7.6	7.2	6.8	1.9	2.1	0.4
Conductivity ($\mu S\,cm^{-1}$)	45	20	53	89	103	30	28	715	322	283
pH	6.6	6.4	6.3	6.8	7.2	6.8	6.7	7.2	7.2	7.1
TDS ($g\,L^{-1}$)	29.4	13.4	22.6	57.4	66.5	19.3	18.1	457.8	206.1	182
Turbidity (NTU)	5.1	4.2	4.7	19.5	11.1	13.2	7.3	45.3	53.2	60.4
TN ($mg\,L^{-1}$)	0.65	0.18	0.24	1.29	1.41	0.93	1.72	38.32	14.87	10.17
TP ($mg\,L^{-1}$)	0.007	0.008	0.012	0.16	0.062	0.017	0.034	2.965	1.106	0.746
Nitrate ($\mu g\,L^{-1}$)	27.46	175.05	524.86	964.3	1473.58	242.49	96.69	2140.22	316.26	714.4
Phosphate ($\mu g\,L^{-1}$)	<2	<2	4.07	83.81	12.77	<2	<2	19.88	142.53	248.66
Ammonium ($\mu g\,L^{-1}$)	7.84	91.62	12.05	757.66	629.27	28.63	11.75	609.38	5492.55	2547.22
Sulphate ($mg\,L^{-1}$)	0.07	1.99	0.69	6.32	6.18	1.81	0.27	2.69	14.43	5.48
Sodium ($mg\,L^{-1}$)	1.12	2.2	1.22	6.64	4.99	1.64	1.49	6.02	12.81	15.08
Potassium ($mg\,L^{-1}$)	0.89	0.63	0.98	2.17	1.67	0.57	0.59	1.43	4.26	2.88
Magnesium ($mg\,L^{-1}$)	0.56	0.49	0.66	1.06	1.4	0.59	0.58	1.36	2.42	1.31
Calcium ($mg\,L^{-1}$)	1.03	1.55	1.07	4.33	7.07	2.41	1.87	5.92	10.99	6.70
Fluoride ($\mu g\,L^{-1}$)	38.84	46.58	28.93	57.79	125.21	35.67	24.29	175.37	212.61	131.56
Chloride ($mg\,L^{-1}$)	1.51	4.32	2.34	16.54	9.34	2.39	2.12	11.29	18.3	22.21
Depth (m)	0.2	0.3	0.4	0.4	0.3	0.4	0.2	0.5	0.3	0.3
Velocity ($m\,s^{-1}$)	2.5	2.8	2.6	2.7	1.4	2.9	2.23	3.5	2.4	2.34
Cr ($mg\,L^{-1}$)	0.01	0.01	0.01	0.01	<0.007	0.01	0.02	0.03	0.03	0.03
Cu ($mg\,L^{-1}$)	0.002	0.003	0.004	0.006	0.003	0.002	0.005	0.029	0.008	0.012
Fe ($mg\,L^{-1}$)	3.04	0.35	0.5	0.26	0.48	0.29	0.43	0.45	1.02	0.79
Cd ($mg\,L^{-1}$)	0.001	0.001	0.002	0.002	<0.001	<0.001	0.002	<0.001	0.005	0.004
Pb ($mg\,L^{-1}$)	<.01	<0.01	0.02	0.01	<0.01	<0.01	<0.01	0.02	0.01	0.02

bidity, TN, TP, most of metals increased significantly downstream (ANOVA, $p < 0.05$) while DO and percentage riparian vegetation cover decreased significantly downstream (ANOVA, $p < 0.05$). The concentrations of all the ions in water increased significantly downstream (ANOVA, $p < 0.05$) (Table 1).

3.2. Indices

The PDI scores based on all the substrates showed significant correlations ($p < 0.05$) with physical and chemical variables (Table 2). Insignificant differences (ANOVA, $p > 0.05$) in the PDI scores based on different natural substrates were recorded, with all substrates classifying the sites into to the same categories (Fig. 2). Sites 1, 2, 3 and 4 were classified as acceptable; sites 5, 6 and 7 were classified as bad; while sites 8, 9 and 10 were classified as very bad. Though there were no significant differences (ANOVA, $p > 0.05$) between natural and artificial substrates, classification of site 1 and 2 was different between the two substrates. Based on all natural substrates, these sites were classified as acceptable while based on artificial substrates they were classified as good. Correlations between the PDI scores from artificial substrates and physical and chemical variables were also generally lower compared to those

Table 2
Correlation between the PDI scores from different substrates and water quality variables recorded in the study area.

Variable	PDI					
	Epipelon	Epipsammon	Epilithon	Epihyton	Bricks	Glass
Conductivity ($\mu S\,cm^{-1}$)	0.94	0.92	0.88	0.87	0.96	0.77
DO ($mg\,L^{-1}$)	−0.91	−0.92	−0.87	−0.88	−0.85	−0.72
BOD_5 ($mg\,L^{-1}$)	0.94	0.95	0.91	0.90	0.86	0.73
pH	0.67	0.64	0.69	0.66	0.59	0.52
Turbidity (NTU)	0.82	0.77	0.76	0.77	0.84	0.80
TDS ($g\,L^{-1}$)	0.93	0.92	0.87	0.85	0.95	0.66
TN ($mg\,L^{-1}$)	0.86	0.88	0.80	0.76	0.77	0.44
TP ($mg\,L^{-1}$)	0.85	0.88	0.80	0.75	0.78	0.41
Fluoride ($\mu g\,L^{-1}$)	0.93	0.96	0.93	0.91	0.86	0.67
Chloride ($mg\,L^{-1}$)	0.93	0.92	0.87	0.88	0.90	0.83
Phosphate ($\mu g\,L^{-1}$)	0.78	0.73	0.70	0.73	0.80	0.83
Sulphate ($mg\,L^{-1}$)	0.87	0.84	0.88	0.88	0.91	0.75
Sodium ($mg\,L^{-1}$)	0.93	0.93	0.88	0.88	0.88	0.80
Ammonium ($\mu g\,L^{-1}$)	0.89	0.87	0.87	0.86	0.86	0.67
Potassium ($mg\,L^{-1}$)	0.94	0.93	0.90	0.88	0.93	0.75
Magnesium ($mg\,L^{-1}$)	0.93	0.95	0.96	0.93	0.92	0.65
Calcium ($mg\,L^{-1}$)	0.93	0.93	0.97	0.96	0.91	0.71
Cr ($mg\,L^{-1}$)	0.65	0.64	0.63	0.63	0.79	0.73
Cu ($mg\,L^{-1}$)	0.91	0.93	0.87	0.86	0.80	0.67
Fe ($mg\,L^{-1}$)	0.86	0.86	0.81	0.81	0.86	0.77
Cd ($mg\,L^{-1}$)	0.89	0.89	0.82	0.81	0.79	0.61
Pb ($mg\,L^{-1}$)	0.89	0.89	0.83	0.82	0.80	0.62
Temperature °C	0.85	0.86	0.83	0.82	0.80	0.47

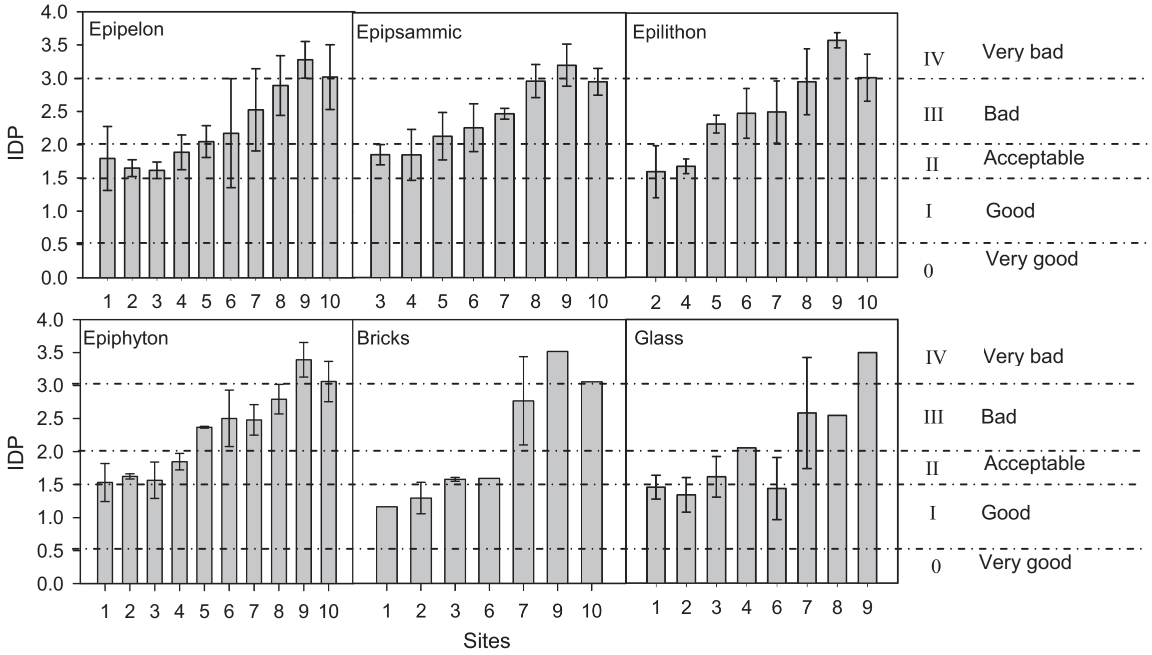

Fig. 2. The Pampean Diatom Index (the PDI) based on different substrates. The water quality classes and significance are indicated on the right side of the graph. Some natural substrates were not available on all the sampling sites while artificial substrate could not be recovered some sites.

between the PDI scores from natural substrates and physical and chemical variables.

4. Discussion

Significant correlations between the PDI scores from different substrates and physical and chemical characteristics of streams recorded in this study indicates the success with which the PDI based on different substrates may be used to reflect changes in ecological conditions of lotic systems in the study area. The PDI scores based on all the six substrates (natural and artificial) classified the sampling sites into roughly similar categories. This shows that all the substrates are equally useful for water quality assessment as they provide relatively similar accuracy of water quality assessment. This is supported by other studies in which values of trophic and saprobic diatom indices did not differ whether they were derived from epilithon, epipelon, or epiphyton (Rott et al., 1998; Kitner and Poulí-Čková, 2003). This is also supported by Potapova and Charles (2005) who found out that benthic diatom-based water quality inference models developed from data sets representing different substrates did not differ significantly in their ability to infer water chemistry.

Since the PDI scores based on all the six substrates produced similar results and diatom communities were also similar among substrates in this study (Bere and Tundisi, 2011), results of the PDI-based water quality assessment based on different substrates appear interchangeable. In the light of these results, the PDI can be applied to habitats other than epipelic, and is applicable to regions other than the Pampas of Argentina from where it was developed. While sampling standard substrates is a desirable way to eliminate the possible influence of substrate, a single preferred substrate type may not be available at all sites as in the case of some of the sites sampled where no stone could be encountered. In such cases, any single available habitat should be sampled at each site, maintaining substrate uniformity as much as possible. Thus, resources should be invested in collecting single samples from as many sites as possible, rather than in sampling multiple substrates from fewer sites. The choice of substrate sampled should not affect accuracy of the PDI-based water quality assessments.

Discrepancies in classification of sites based on the PDI from natural and artificial substrates were observed. The flora of artificial substrates is an artificial assemblage selected by physical and chemical properties of the substrate (e.g., texture, chemical composition) and perhaps positioning of substrate in relation to the currents. The species found on the glass substrate were mostly those with a tight attachment habit (Bere and Tundisi, 2011). This is likely to affect the interpretation of water quality management results as the absence of a particular species on a given site is likely to be mistaken for the effects of the perturbations under study. However, in this study, the PDI scores from artificial substrates were equally correlated to environmental variables (Table 2) as in the case of natural substrates. In situations where it is difficult to encounter one substrate among sampling sites and variation in community structure are expected as other studies have demonstrated (e.g., Lowe and Pan, 1996; Kelly et al., 1998), the use of artificial substrate can be an alternative option with the advantage that substratum is standard at all sampling sites and time of exposure can be controlled (Round, 1991).

However, Komárek and Sukacová (2004) have shown that introduced artificial substrates are often characterized by diatom communities indicative of more successional processes than water quality. They recommend leaving artificial substrate for a year before sampling to allow the diatom communities to progress from a colonization community to a stable community reflecting environmental conditions and typical of natural communities. This prevents rapid estimation of water quality such as can be obtained within hours of direct sampling of natural substrates. Besides, use of artificial substrate requires apparatus to be fixed in the river and there are often losses, as in this case, and random sampling is not possible (Round, 1991; Descy and Coste, 1991). This further complicates the use of artificial substrate for water quality management. Sampling of natural substrates is thus highly recommended compared to artificial substrates.

In conclusion, it can be said that the PDI can be applied to habitats other than epipelic, and is applicable to the study area. The choice of substrate sampled may not affect accuracy of the PDI-based water quality assessment.

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