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A Macroinvertebrate-Based Multimetric Index for Assessing Ecological Condition of Forested Stream Sites Draining Nigerian Urbanizing Landscapes

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Abstract: Urban pollution is increasing at an alarming rate within the catchments of forested riverine systems in sub-Saharan Africa, Nigeria inclusive. Assessing the impact of pollution in riverine systems in the Niger Delta region is still within the use of physico-chemical variables and biota-based assemblage. In covering this important gap in freshwater biomonitoring, we developed a macroinvertebrate-based multimetric index (MMI) that would be useful in monitoring, assessing, and managing forested riverine sites affected by urban pollution. We collected macroinvertebrates and physico-chemical samples monthly at 20 sites in 11 streams. Physico-chemical variables were analysed using standard methods while a kick sampling procedure was employed in collecting macroinvertebrates. The physico-chemical variables were used to classify the sites into three disturbance categories: least-impacted sites (LIS), moderately impacted sites (MIS), and heavily impacted sites (HIS). Fifty-nine candidate macroinvertebrate metrics were selected and screened for developing our MMI. We employed sensitivity, seasonality, repeatability and redundancy tests, and metric scoring in screening and arriving at the final metrics for the MMI development. Five metrics were finally selected for the MMI development: Trichoptera abundance, %Chironomidae+Oligochaeta, Coleoptera richness, Simpson diversity, and Shannon–Wiener index. Correlation in the selected metrics with physico-chemical variables showed that Simpson diversity was negatively correlated with pH in the MIS and Coleoptera richness was positively correlated with dissolved oxygen (DO) and water depth in the LIS. Nitrate, biochemical oxygen demand (BOD), conductivity, and water temperature were negatively correlated with %Chironomidae+Oligochaeta in the HIS. This MMI can aid river and stream managers in assessing the ecological conditions of rivers and streams in the Niger Delta region of Nigeria.

Keywords: taxonomic and trait-based biomonitoring; anthropogenic disturbances; site categorisation; structural and functional ecology; Chironomidae; Trichoptera; diversity

1. Introduction

Anthropogenic activities are increasing at an alarming rate in the catchments of forested riverine systems in sub-Saharan Africa as a result of increased urban development, driven by rural–urban migration [1,2]. It has been reported that urban development negatively affects the ecological condition of riverine systems, including deterioration of water quality and physical habitat structure, as well as altered biological structure and function [2–4]. Our study area, the Niger Delta region of Nigeria, used to be home to numerous inland waters, mangrove swamps, and creeks with thickly forested catchments. However, recently the forested catchments have been subjected to increasing urban activities and most of the forested riverine systems in the area are now draining partially urbanised catchments [5].

Forests are important natural components in river catchments in the Niger Delta and throughout the tropical rain forest belt of Nigeria. Many forested rivers and streams within the Niger Delta are influenced naturally by processes occurring as a result of forest dominance, such as shading, leaf litter, and hydrological predictability [6,7]. Allochthonous food resources and shading resulting from the forested riparian zones are critical for determining the assemblage structure and function of naturally forested riverine systems [6,7]. The river continuum concept from Vannote et al. [6] predicts a pattern for forested rivers and streams where soluble organic materials, coarse particulate organic matter (CPOM), and dominance of macroinvertebrate shredders and collector–gatherers are common. The shredders and collector–gatherers accelerate the breakdown and transformation of CPOM into fine particulate organic matter (FPOM) [6,8]. However, urbanisation reduces the dense tree canopy and increases water temperatures [2], thereby reducing the dominance of shredders and collector–gatherers [9]. The rapid urbanisation of the Niger Delta region is of great concern to river managers. Therefore, developing cost-effective biomonitoring tools that would be useful in monitoring the effects of urbanisation and urban pollution on these systems is pertinent.

In developing biomonitoring indices for riverine systems, a number of approaches have been employed globally [10–13]. These approaches include single biotic indices, multivariate analyses, functional feeding groups, and structure- and trait-based multimetric indices (MMIs) [2,10–13] and these approaches have their advantages and disadvantages. Bonada et al. [10] explicitly outlined the advantages and disadvantages of biotic assessment approaches. The advantages of some of these approaches are as follows: (i) the single biotic index approach awards a pollution sensitivity score to each taxon and averages the total for a sampled site, (ii) multivariate analyses are developed by comparing control sites with impaired sites, (iii) the functional approach is based on the feeding habits of biota, (iv) the trait-based approach takes into account physiological, behavioural, and biological characteristics of taxa, and (v) multimetric indices (MMIs) incorporate all or most of the approaches into a single score [10–12]. The MMIs potentially include biotic indices, such as taxonomic, trait, and functional metrics, as well as abundance, composition, richness, and diversity and, therefore, have been reported to be more robust and effective than other biomonitoring indicators [4,10,11,14]. The MMIs are more advantageous based on the following premise: the single biotic index score is awarded to only one taxon and can only be used to judge organismal responses to disturbance in a local context. The multivariate approach takes into account one site per time and cannot be used to assess the ecological health of a whole stretch of a riverine system. The functional and trait-based approaches only define the feeding habits and characteristics of taxa despite the fact that they can be employed widely in several geographical regions. However, the MMIs take into account all the approaches, which makes them more robust for the development of biotic indices in most quarters [2–4,10,13,14].

In developing MMIs, aquatic fauna and flora, such as aquatic macrophytes, phytoplankton, diatoms, macroinvertebrates, fish, and birds, have been widely employed globally [13–20]. Among the aquatic fauna and flora employed in developing MMIs, macroinvertebrates have been widely explored globally because of their important position as secondary producers in the aquatic food chain and food web and their sampling ease [13,21–23]. Most MMIs are developed using macroinvertebrate metric measures to assess general water conditions and, usually, for single riverine systems [3,4,11,14]. In the present study, we explored several forested riverine systems draining urban landscapes in the Niger Delta region of Nigeria in a bid to develop an MMI for assessing the deteriorating state of riverine systems. Therefore, we developed a macroinvertebrate MMI for assessing the ecological condition of forested riverine sites draining partially urbanising landscapes in the Niger Delta region of Nigeria.

2. Materials and Methods

2.1. Study Area

We sampled 20 sites in 11 streams within Edo and Delta states of the Niger Delta region of Nigeria (Figures 1 and 2). The study area covers 70,000 km^2 at latitude 5.438000–7.11070 and longitude 5.67800–6.64700 [24]. Two seasons (wet and dry) characterize the area with the wet season spanning from March to September, while the dry season is from October to February [25]. The wet season temperatures range from 15 °C to 25 °C and the dry season temperatures are between 25 °C and 35 °C. The average annual rainfall is 2000 m–3500 mm and the relative humidity is 85% [2,25]. Most of the sites are bordered by forested catchments with patches of urban, industrial, and agricultural activities in some reaches of the streams. Urban, industrial and agricultural activities within the sampled streams included crude oil exploration, logging, fishing, farming, washing, and bathing [26,27]. The Niger Delta contributes the bulk of foreign exchange for Nigeria because it is the crude-oil-rich region in the country, which also drives the urbanisation and industrialisation of the region [24]. However, cities in the region have poor drainage systems and their streams suffer from untreated waste disposal and storm water flows [27].

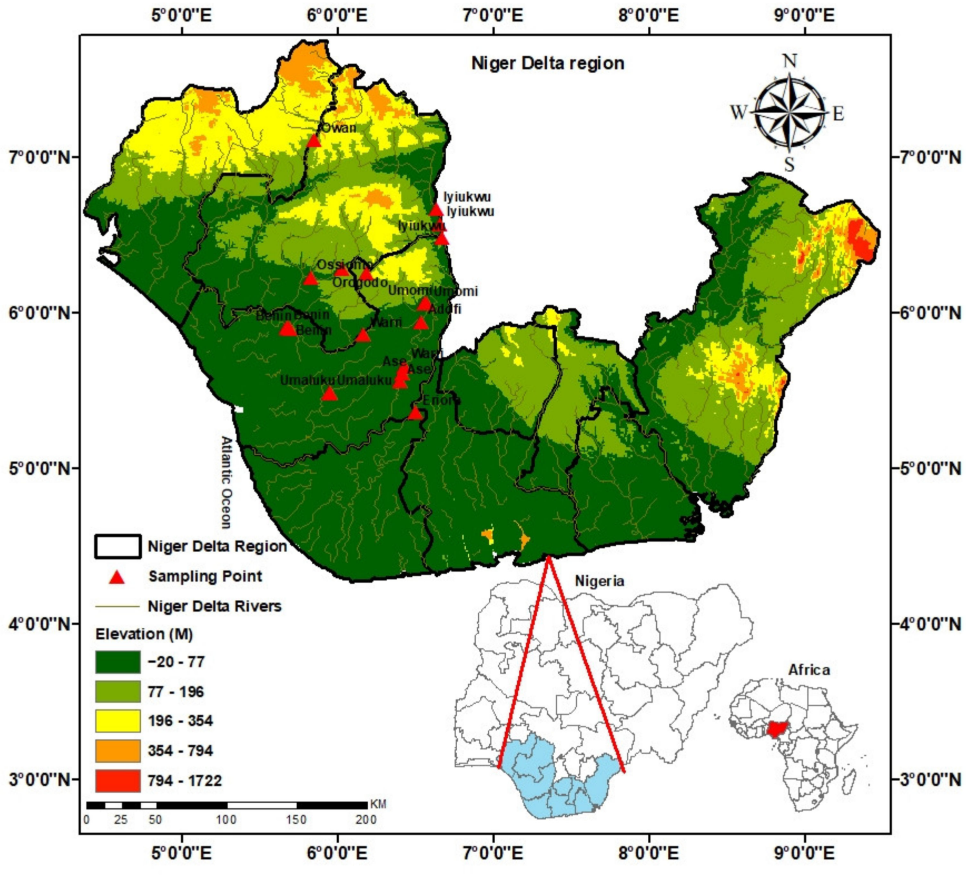

Figure 1. Map of the Niger Delta region of Nigeria showing region elevations (maps of Africa and Nigeria insert).

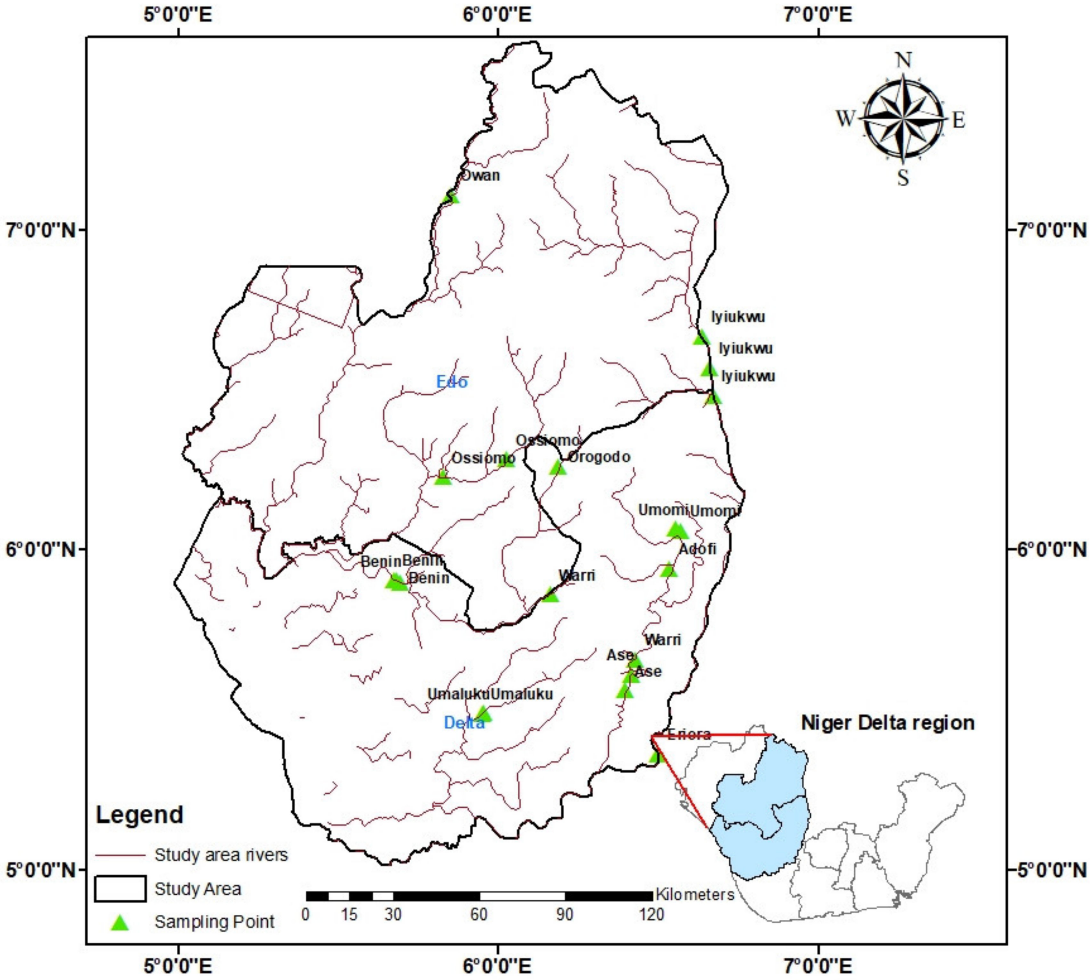

Figure 2. Map of the study area showing the sampling stations (map of the Niger Delta region of Nigeria insert).

2.2. Physico-Chemical and Macroinvertebrate Sampling

Before the commencement of sampling exercise, the coordinates of each site were marked out to ensure that datasets collected were coming from the same site. All sampling instruments and equipment were properly calibrated and examined to ensure accuracy of the samples collected per sampling expedition. Further, as sampling was performed by a research group, briefing was conducted by the lead researcher on each sampling occasion to avoid incongruity in the collections made by each group involved.

Physico-chemical variables and macroinvertebrates were sampled monthly for five years between 2008 and 2012. Mercury thermometer was used to measure water temperature and a metal rod calibrated in centimetres was used to measure water depth. Current velocity was measured following the flotation method [28]. DO, pH, and EC were measured by using a portable HANNA HI9829 multiprobe meter. Three replicate water samples were collected in 500 mL glass bottles on each visit for determining BOD, nitrate, and phosphate, then analysed in the laboratory [29].

Macroinvertebrates were collected using a D-frame kick-net [30] at each site for three minutes. All habitat types present (vegetation, mud, silt, sand, stones) were sampled and then combined into a single composite sample for each site visit [24]. The samples we collected were preserved in 70% alcohol and taken to the laboratory for sorting, identification, and enumeration [24]. Macroinvertebrates were identified to family level by using a stereoscopic microscope at X10 magnification and available keys [31–33].

2.3. Data Analyses

Site Classification

The 20 sites in 11 streams of the forested riverine systems within urban catchments were categorised into three potential impact categories using physico-chemically based classification using a multivariate model: principal component analysis (PCA). The impact categories were least-impacted sites (LISs), moderately impacted sites (MISs), and heavily impacted sites (HISs) (Appendix A Table A1) [34,35]. The PCA was computed using the vegan package version 2.5.4 in R [36,37]. Three sites were classified as LIS, seven as MIS, and ten as HIS (Appendix A Table A1). Details on how the sites were classified into LIS, MIS, and HIS are contained in our previous study [24].

2.4. Macroinvertebrate Metric Selection

Fifty-nine (59) candidate metrics were selected for developing the MMI based on available literature [35,38,39]. The 59 metrics were defined into five measures, namely: abundance, composition, richness, diversity, and traits (Appendix A Table A2). Abundance metrics included absolute abundances of individuals in various macroinvertebrate groups, whereas composition metrics were determined as the relative abundances of groups in the entire sample [3]. Richness metrics were calculated as the absolute number of taxa in macroinvertebrate groups and diversity measures were defined following Clarke and Warwick [40] and Edegbene et al. [35]. Trait metric information was gathered from Krynak and Yates [41] and Edegbene et al. [12]. Trait information was fuzzy coded [42] in which we awarded scores of 0–3 to each trait attribute per taxa, with a score of 0 for taxa with no affinity to a particular trait and 1, 2, and 3 for taxa with low, moderate, and high affinity for a given trait.

2.5. MMI Development

We followed a four-step procedure to select metrics by testing each metric for: (i) sensitivity (discrimination), (ii) seasonality, (iii) repeatability (signal/noise), and (iv) redundancy.

2.5.1. Test for Sensitivity (Discrimination)

We tested the discriminatory potential of metrics by comparing their performance in the LIS, MIS, and HIS [43] by using box and whisker plots. We considered two criteria in selecting metrics that showed discriminatory potential. First, a metric that showed no overlap in the interquartile ranges (IQRs) between LIS and MIS and HIS was considered sensitive [35,43]. Second, if there was overlap in the IQRs but if their medians were outside of the IQRs, such a metric was considered discriminatory [35,43].

To test the significance level of the selected sensitive metrics as per the result from the box and whisker plots, we first performed a Kolmogorov–Smirnov normality test. The test indicated that metrics were not normally distributed; therefore, we used a non-parametric Mann–Whitney (U) test to test for metrics level of significance. Metrics exhibiting a significant difference at $p < 0.05$ between the LIS and the MIS and HIS were retained for further analysis [44]. Box and whisker plots were constructed using Statistica version 13.4.14 (TIBCO Software Inc., Palo Alto, CA, USA, 2018). The Kolmogorov–Smirnov and Mann–Whitney tests were calculated using Palaentological Statistical Package (PAST) [45].

2.5.2. Test for Seasonality

Metrics that were sensitive (discriminatory) were subjected to seasonal stability test. Seasonal stability of metrics was visualized by box and whisker plots and further confirmed by a Kruskal–Wallis test [35,46]. Metrics that discriminated between wet and dry seasons based on the visual observation from box and whisker plots and showed no significant difference ($p > 0.05$) were considered seasonally stable [2,47]. Metric seasonal stability was tested only on LIS samples to avoid confounding urban pollution with seasonal variability [14].

2.5.3. Test for Metric Repeatability (Signal/Noise)

Metric repeatability was tested using the signal (S) to noise (N) ratio, i.e., S:N [48]. The signal value for each metric was arrived at by calculating the metric variance in all the samples from all the sites. On the other hand, the noise value for each metric was obtained by calculating the metric variance in the samples from the least-impacted sites (LISs). Therefore, the repeatability potential of each metric was assessed by dividing the value of signal (S) by that of noise (N). Metrics with high signal-to-noise ratios were considered to be relatively precise (repeatable) and those with low signal-to-noise ratios were considered to be less precise [49]. Following Stoddard et al. [48], metrics with S:N values $\geq$2 were retained.

2.5.4. Test for Metric Redundancy

Metrics are redundant if they convey similar information [35]. A correlation coefficient (Spearman's r) was computed for metrics that passed the seasonal stability test. Metrics with $r \geq 0.78$ were deemed redundant [43].

2.6. Metric Scoring

To integrate metrics with different value ranges into the final MMI, we standardised each metric to a score of 0–10 using the 5th (scoring floor) and 95th (scoring ceiling) percentiles of the LIS values [48,49]. Two steps were followed in awarding either a score of 0 (poor) or 10 (good) to each metric. Metrics that respond negatively to increasing pollution were awarded a score of 10 if they correspond to the 95th percentile of the metric raw values and a score of 0 if they correspond to the 5th percentile of the metric raw values. On the other hand, metrics that respond positively to increasing pollution were awarded a score 0 if they correspond to the 95th percentile of the metric raw values, whereas a score of 10 was awarded if they correspond to the 5th percentile of the metric raw values [50]. In integrating the selected metrics into the final MMI, a metric with raw value of 0 was given a value of 0, then metric with raw value of >0–10 was given a value of 5 and metric with raw value of >10 was given a value of 10. Similar approach had earlier been used by Huang et al. [49] and Edegbene [51] to award either a score of 0 or 1 to metric raw values. In scoring the metric continuously in the study we adopted the following procedures: for metrics that decrease with pollution, the raw score of the 5th percentile was subtracted from the raw score of 95th percentile, divided by 5 and scored continuously, and for metrics that increase with pollution the raw score of the 5th percentile was added to the raw score of 95th percentile, divided by 5 and scored continuously.

The final MMI score was computed following the method earlier used by Klemm et al. [52] by summing the scores of all metrics and dividing by the total number of metrics. Hence, the final MMI score was within a range of 0–10. Finally, we assigned three biological condition categories to the final MMI scores, namely good, fair, or poor. The three condition categories were adopted as had earlier been argued by Ganasan and Hughes [53] that many ecological categories/classes can lead to confounding interpretation of final MMI scores and, thus, affect stream managers' decisions on water quality. Further, good, fair, and poor condition categories were deemed appropriate for the MMI biological condition categories as the riverine systems used in this study are partially draining urbanising landscape; hence, there cannot possibly be an excellent or very good biological condition category.

2.7. Correlating Metrics with Physico-Chemical Variables

A test of unimodality and linearity using detrended correspondence analysis (DCA) showed a gradient length < 3, which indicated that the metric data were linear [54]. Therefore, the final selected metrics were correlated with selected physico-chemical variables via multivariate redundancy analysis (RDA) [55]. Physico-chemical variables that were highly multi-colinear ($r \geq 0.80$) were removed from the RDA model analysis. Furthermore, a test of global significance (Monte Carlo) test with 999 permutations was used to ascertain the level of significant differences between the first two RDA axes [56]. The RDA and Monte Carlo tests were performed in R (vegan package) [36,37].

3. Results

3.1. Metric Screening

Of the 59 candidate metrics tested, only 14 showed discriminatory potential (Appendix A Table A3) and 12 were seasonally stable. Among the 12 seasonally stable metrics, only three were deemed to be both repeatable (Table 1) and not redundant (Table 2); hence they were retained for MMI scoring (Figures A1 and A2 in Appendix A). In addition to the three non-redundant metrics retained, two more metrics (Trichoptera abundance and %Chironomidae+Oligochaeta) were included in the MMI scoring for fair representation of all the metric measures selected for this study, except metrics in the trait measure that did not scale through the test for seasonality and, hence, were excluded from the tests for repeatability and redundancy. Further, Trichoptera abundance and %Chironomidae+Oligochaeta were included in the MMI scoring because they were deemed repeatable following the signal/noise test conducted.

Table 1. Repeatability (signal/noise) of macroinvertebrate metrics.

Metrics	Signal (N)	Noise (N)	S/N	Metric Status
Tri Abun	285.3	171.4	1.66	Rejected
EPT/Chi Abun	27	56.6	0.48	Rejected
%Odo	47.5	30.2	1.57	Rejected
%Chi	222.31	131.54	1.69	Rejected
%Chi+Oli	256.5	19.9	12.89	Retained
%Dip	389.5	17.3	22.50	Retained
%Mol+Dip	409.1	19.3	21.20	Retained
Col Rich	4.75	2.3	2.07	Retained
Col+Hem Rich	10.42	5.27	1.97	Rejected
Sha Div	0.22	0.059	3.73	Retained
Sim Div	0.0028	0.00022	12.73	Retained
Mar Ind	2.37	1.33	1.78	Rejected

Table 2. Redundancy of macroinvertebrate metrics as revealed by Spearman's rank correlation ($r \geq 0.78$, $p < 0.05$).

Metrics	%Chi+Oli	%Dip	%Mol+Dip	Col Rich	Sim Div	Sha Div
%Chi+Oli	0.00	2.14×10^{-7}	2.14×10^{-7}	**0.89008**	0.046107	0.079317
%Dip	**0.8853**	0.00	0.00	0.7111	0.038753	0.034475
%Mol+Dip	**0.8853**	1.00	0.00	0.7111	0.038753	0.034475
Col Rich	−0.03302	0.088345	0.088345	0.00	0.018082	0.00906
Sim Div	0.45071	0.46519	0.46519	0.52258	0.00	1.77×10^{-11}
Sha Div	0.4015	0.47461	0.47461	0.5675	0.96087	0.00

Note: None of the metrics were significant at $p < 0.05$.

3.2. MMI Scoring

As with metric scoring, the 5th percentile was used as the scoring floor and 95th percentile as the scoring ceiling using the metric values of the LIS (Table 3). The metric values of LIS were used to avoid confounding effects of pollution on the metrics selected. Four of the retained metrics respond negatively to increasing pollution, namely: Trichoptera abundance, Coleoptera richness, Simpson diversity, and Shannon–Wiener index, and they were, thus, awarded a score of 10, corresponding to the 95th percentile of the raw values and 0, corresponding to the 5th percentile of the raw values. Only one metric (%Chironomidae+Oligochaeta) that responds positively to increasing pollution was awarded a score of 10, corresponding to the 5th percentile of the raw value and 0, corresponding to the 95th percentile of the raw value. Therefore, metric scoring of the retained metrics in Table 3 was scored following the score distribution patterns below.

Table 3. Metric values and scoring.

Metrics	Percentiles	
	5th (Scoring Floor)	95th (Scoring Ceiling)
Trich Abun	1.00	14.1
%Chi+Oli	1.27	15.20
Col Rich	3.95	8.00
Sim Div	0.91	0.96
Sha Div	2.70	3.50

For metrics that decrease with pollution, the raw score of the 5th percentile was subtracted from the raw score of the 95th percentile, divided by 5 and scored continuously as follows: Trichoptera abundance LIS raw score corresponding to 5th percentile was 1.00 and was scored as 0 and 95th percentile was 14.1 and was scored 10. Trichoptera abundance raw score of <1 = 0. Trichoptera abundance raw score of 1–3.62 was scored as 1/5(10) = 2. Trichoptera abundance raw score of 3.62–6.24 was scored as 2/5(10) = 4. Trichoptera abundance raw score of 6.24–8.86 was scored as 3/5(10) = 6. Trichoptera abundance raw score of 8.86–11.48 was scored as 4/5(10) = 8. Trichoptera abundance raw score of 11.48–14.1 was scored as 5/5(10) = 10.

Coleoptera richness LIS raw scores corresponding to the 5th and 95th percentiles ranged from 3.95 (scored 0) to 8.00 (scored 10), Coleoptera richness raw score of <3.95 = 0. Coleoptera richness raw score of 3.95–4.76 was scored as 1/5(10) =2. Coleoptera richness raw score of 4.76–5.57 was scored as 2/5(10) = 4. Coleoptera richness raw score of 5.55–6.38 was scored as 3/5(10) = 6. Coleoptera richness raw score of 6.38–7.19 was scored as 4/5(10) = 8. Coleoptera richness raw score of 7.19–8.00 was scored as 5/5(10) = 10.

The Simpson diversity LIS raw scores corresponding to the 5th and 95th percentile values range from 0.91 (scored as 0) to 0.96 (scored as 10). Simpson raw score < 0.91–0.91 = 0. Simpson raw score of 0.92 was scored as 1/5 (10) = 2. Simpson raw score of 0.93 was scored as 2/5(10) = 4. Simpson raw score of 0.94 was scored as 3/5(10) = 6. Simpson raw score of 0.95 was scored as 4/5(10) = 8. Simpson raw score of 0.96 and above was scored as 5/5(10) = 10.

The Shannon diversity LIS raw scores corresponding to the 5th and 95th percentile values range from 2.70 (scored as 0) to 3.50 (scored as 10). Shannon diversity LIS raw score < 2.70 = 0. Shannon diversity raw score of 2.86 was scored as 1/5 (10) = 2. Shannon diversity raw score of 3.02 was scored as 2/5(10) = 4. Shannon diversity raw score of 3.18 was scored as 3/5(10) = 6. Shannon diversity raw score of 3.34 was scored as 4/5(10) = 8. Shannon diversity raw score of 3.5 and above was scored as 5/5(10) = 10.

For metrics that increase with pollution, the raw score of the 5th percentile was added to the raw score of the 95th percentile, divided by 5 and scored continuously as follows: The %Chironomidae+Oligochaeta LIS raw scores corresponding to the 5th and 95th percentile values range from 1.27% (scored as 10) to 15.20% (scored as 0). The %Chironomidae+Oligochaeta raw score of >1.27–3.294% was scored as -3.294/15(10) + 10 = 7.804. The %Chironomidae+Oligochaeta raw score of 6.588% was scored as −6.588/15(10) + 10 = 5.608. The %Chironomidae+Oligochaeta raw score of 9.882% was scored as −9.882/15(10) + 10 = 3.412. The %Chironomidae+Oligochaeta raw score of 13.176% was scored as −13.176/15(10)

+ 10 = 1.216. The %Chironomidae+Oligochaeta raw score of >13.176% and 15.2 was scored as −15.2/15(10) + 10 = 0.00.

Finally, we assigned three biological categories based on the site MMI scores: poor (<2.0), fair (2.0–4.0), and good (>5.0).

3.3. Correlating MMI Metrics with Physico-Chemical Variables

The first and second axes of the RDA model explained 81.93% and 18.07% of the total variance, respectively, but the Monte Carlo test indicated that the first two axes of the RDA were not significantly different ($p > 0.05$). Nonetheless, Simpson diversity was negatively correlated with pH in the MIS along Axis 1 and Coleoptera richness was positively correlated with DO and water depth in the LIS along Axis 1 (Figure 3). Nitrate, BOD, conductivity, and water temperature were positively correlated with %Chironomidae+Oligochaeta in the HIS along Axis 2.

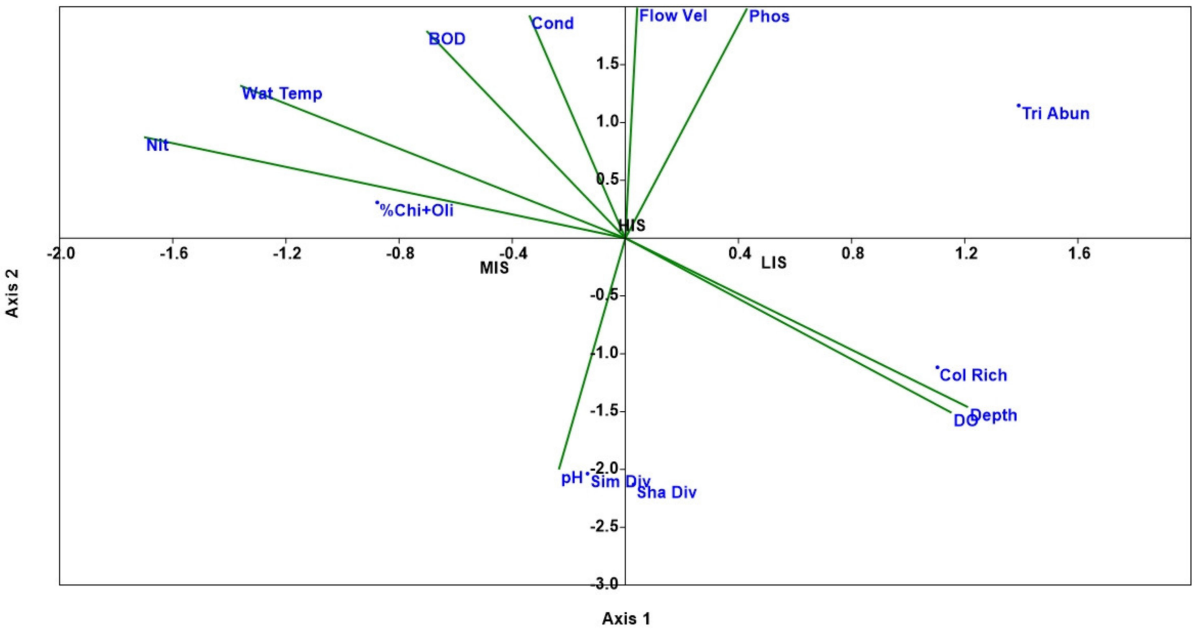

Figure 3. Redundancy analysis of the correlation between MMI metrics and physio-chemical variables. Abbreviations: Physio-chemical variables: Wat Temp = water temperature, Cond = conductivity, Flow Vel = flow velocity, Nit = Nitrate, Phos = phosphate, DO =dissolved oxygen, BOD = biochemical oxygen demand. *Metrics:* Tri Abun = Trichoptera abundance, Col Rich = Coleoptera richness, %Chi+Oli = %Chironomidae+oligochaete, Sim Div—Simpson diversity, Sha Div = Shannon–Wiener diversity.

4. Discussion

In the present study, we developed a macroinvertebrate-based multimetric index (MMI) for assessing forested riverine sites draining partially urbanising catchments in the Niger Delta region of Nigeria. Fifty-nine (59) candidate metrics were selected for the development of MMI and, of the fifty-nine metrics, only five metrics in the measures of abundance (composition, richness, and diversity) were retained for final integration into the MMI. The test for discrimination (sensitivity) revealed 14 of the selected metrics to satisfactorily discriminate LIS from MIS and HIS and these sensitive metrics were mainly in the measures of composition and richness. The high composition and richness measures of macroinvertebrates can be inferred from the fact that streams that are least impacted are known to support an array of diverse macroinvertebrate communities because such rivers provide heterogeneous habitats, favouring a diverse niche partitioning [22]. However, rivers that have been impacted as a result of anthropogenic activities (e.g., urbanisation), diverse composition, and richness potentials of the inhabitant aquatic biota (e.g., macroinvertebrates) tend to be sensitive, thus, indicating why they proved sensitive in the present study. Composition and richness measures have continually been included in most multimetric indices developed for aquatic systems based on the fact that they prove to be highly sensitive [56,57]. Other studies have also reported the effectiveness of metrics in the measures of abundance, composition, and richness, hence, their continuous integration into multimetric indices developed for biomonitoring freshwater ecosystems [4,14,39,49,58–60]. Taxa of macroinvertebrates, which comprise metrics in the abundance, composition, and richness categories, as well as functional ecology have been asserted to structure the community balance of the freshwater ecosystem [39,49,59,60]. For instance, Huang et al. [49] developed and applied benthic macroinvertebrate-based multimetric indices for the assessment of streams and rivers in the Taihu Basin, China. They employed metrics, such as richness, composition, diversity and evenness, pollution tolerance, and functional feeding groups, and they concluded the MMI developed proved important for ecological biomonitoring and management.

In this study, we integrated five metrics into the final MMI and they include Trichoptera abundance, Coleoptera richness, Simpson diversity, Shannon–Wiener index, and %Chironomidae+Oligochaeta, although, Trichoptera abundance and %Chironomidae+Oligochaeta were either non-repeatable or redundant. Trichoptera abundance was not repeatable while %Chironomidae+Oligochaeta was redundant. Trichoptera abundance and %Chironomidae+Oligochaeta were included in the MMI scoring, owing to the fact that they are ecologically significant [3,14]. Earlier studies integrated metrics that were redundant into an MMI following similar criteria, which was hinged on fair representation of all metric measures selected for development of MMI [2,3,47]. Taxa in the Order Trichoptera have been reported by several authors as being sensitive to pollution while taxa in the Chironomidae and Oligochaeta are tolerant of pollution [2,3,14,27,34].

In the tropics, Trichoptera has been documented to usually present a critical biological feature based on their high affinity to increase dissolved oxygen concentration as well as their ability to build their case with leaves and litters [46]. Thus, forested systems in the tropics present an ideal habitat for species of Trichoptera that build their case with leaves and litters. This is due to the availability of appropriate materials in forested systems for building case and further serves as a food source for them, as most Trichopterans are shredders and collector–gatherers [25]. Since Trichopterans are intolerant of dissolved oxygen depletion, the non-availability of case-building materials and food sources would make the Trichoptera disappear in the face of such ecological alteration. Trichopterans are usually one of the first sets of macroinvertebrate taxa to reduce in abundance in response to ecological degradation occasioned by human activities along the catchments of riverine systems, hence, their quick disappearance in the face of anthropogenic disturbance (e.g., urban pollution). This characteristic may be the reason Trichopteran abundance metric in this study proved sensitive and further scaled through seasonality test and, finally, integrated into the MMI. Similar studies documented the negative response of metrics in the categories of Trichoptera abundance, Coleoptera richness, and diversity indices to pollution [3,35]. Aside from Trichoptera abundance, other metrics, such as %Chironomidae+Oligochaeta, %Chironomidae, and Coleoptera richness, have also been selected for integration into MMI because of their significance in defining ecological status [60]. Among these, Chironomidae and Oligochaeta have been known to respond positively to increasing anthropogenic activities in freshwater systems [14]. This was confirmed by %Chironomidae+Oligochaeta correlation with nutrient (nitrate), conductivity, BOD, and water temperature on the RDA we performed in the present study. Other authors had earlier integrated our selected metrics into multimetric indices, e.g., [3,35]. In recent times, studies on the use of Chironomidae and other tolerant taxa, such as Oligochaetes, in flowing water ecosystems as an indicator of pollution have received attention. Chironomidae (Diptera) and Oligochaetes (Annelida) preponderance in ecosystems rich in increasing nutrient concentration and depleting dissolved oxygen concentration have been reported by several authors, e.g., [23,49], to be useful indicators for assessing organic pollution in riverine systems. The possession of haemoglobin by Chironomidae makes them tolerant of sites with depleted oxygen concentration as they use haemoglobin molecules to trap oxygen within their body in the event of reduced dissolved oxygen in water [25,34], hence, their importance in assessing polluted sites in riverine systems. Other genera of the order Diptera (e.g., *Eristalis* in the family Syrphidae) possess extensible breathing tubes for capturing atmospheric oxygen in the face of depleted dissolved oxygen in polluted sites [46]. Further, Oligochaetes have moist skin, which enables them to extract atmospheric oxygen, hence, their ability to survive in polluted sites. These features possessed by this group of macroinvertebrates make them important taxa for developing indices of biotic integrity and other biomonitoring tools globally [22,25,34,35,46,49].

5. Conclusions

In this study, we developed a multimetric index (MMI) for forested riverine sites draining partially urbanising landscape in the Niger Delta region of Nigeria. Five metrics in the measures of abundance, composition, richness, and diversity were finally selected and integrated into the MMI. Of the five integrated metrics, four were adjudged to be sensitive to pollution, namely: Trichoptera abundance, Coleoptera richness, Simpson diversity, and Shannon–Wiener diversity. On the other hand, the remaining metric %Chironomidae+Oligochaeta was pollution tolerant. The combination of both sensitive and tolerant metrics in the MMI we developed made it robust and deemed effective for biomonitoring forested riverine systems draining partially urbanising catchments. Forested streams and rivers in the Niger Delta region have been urbanising tremendously and MMI of this kind is pertinent to assess the level of perturbation the streams are subjected to. We recommend the developed MMI for biomonitoring forested rivers and streams impacted by urban pollution in the Niger Delta region of Nigeria. Further, we recommend a more sophisticated MMI to be developed for the Niger Delta region, which will take into account more sampling sites along the stretch of the riverine systems in the region.

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Data Availability Statement: Datasets used in the study are available at http://www.mdpi.com/2073-4441/12/11/3111/s1 (accessed 21 July 2021).

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Potential impact categories classification and mean (range) of physico-chemical conditions of forested river sites draining partially urbanized landscapes in the present study.

					Mean Physico-Chemical Variables								
Rivers	**Site Codes**	**LIS**	**MIS**	**HIS**	**Water Temperature (°C)**	**Depth (m)**	**Flow Velocity (ms^{-1})**	**Conductivity (μscm^{-1})**	**DO (mgL^{-1})**	**BOD (mgL^{-1})**	**pH**	**Nitrate (mgL^{-1})**	**Phosphate (mgL^{-1})**
Warri	Wa2	X			22.3 (21.0–23.4)	0.91 (0.63–1.12)	0.14 (0.1 –1.7)	9.5 (8.11–11.5)	5 (4.3–5.62)	0.9 (0.04–1.24)	7 (6.8 –7.2)	0.1 (0.09–0.12)	0.1 (0.07–0.12)
Warri	Wa1	X			25.2 (23.4–28.0)	0.95 (0.65–1.31)	0.14 (0.13–0.22)	9.9 (8.02–12.1)	8.8 (7.0–10.8)	1 0.72–1.1)	7 (6.6–7.2)	0.09 (0.06–0.12)	0.09 (0.06–0.11)
Adofi	Ad	X			21.1 (20.2–21.5)	0.56 (0.37–0.74)	0.27 (0.24–0.35)	11.7 (9.8–13.2)	8 (7.06–9.2)	2.3 (1.9–2.8)	6.7 (5.5–7.1)	0.5 (0.42–0.53)	0.4 (0.38–0.42)
Orogodo	Or		X		26 (24.5–28.4)	0.66 (0.25–0.75)	0.1 (0.09–0.17)	13.6 (12.0–14.3	7.4 (5.0–7.8)	2.3 (2.1–2.6)	6.4 (6.1–7.9)	2.8 (0.8–3.4)	0.01 (0.009–0.013)
Ase	As2		X		24.9 (22.3–25.0)	0.54 (0.34–0.61)	0.27 (0.17–0.32)	15.3 (12.6–16.4)	6.1 (5.5–6.3)	2.4 (1.8–2.8)	7.3 (5.2–8.3)	1.3 (0.6–2.6)	0.15 (0.12–0.17)
Iyiukwu	Iy3		X		27.8 (25.6–28.6)	0.45 (0.23–0.51)	0.23 (0.09–0.32)	15.4 (11.5–16.8)	6 (5.2–6.9)	2.6 (1.9–2.9)	6.4 (6.2–6.7)	0.03 (0.01–0.05)	2.2 (1.3–2.9)
Iyiukwu	Iy1		X		27.4 (21.7–29.3)	0.59 (0.15–0.62)	0.2 (0.12–0.24)	16.6 (13.2–17.4)	6 (5.6–6.4)	2.8 (1.6–3.2)	5.6 (4.7–6.2)	0.4 (0.01–0.7)	2.8 (0.08–3.5)
Ase	As1		X		25.3 (22.3–26.0)	0.7 (0.51–0.82)	0.22 (0.07–0.28)	17 (13.0–18.5)	5.4 (5.2–5.8)	3.3 (0.98–4.6)	6.7 (5.6–7.9)	2.3 (0.06–2.8)	0.13 (0.03–0.16)
Iyiukwu	Iy2		X		27.6 (24.6–28.2)	0.63 (0.25–0.68)	0.2 (0.08–0.24)	17.4 (11.2–18.0)	6 (5.5–6.8)	3.2 (2.4–3.8)	5.6 (4.3–6.1)	0.04 (0.01–0.08)	2.5 (1.2–2.9)
Benin	Be3		X		24.7 (21.5–25.5)	0.66 (0.56–0.72)	0.14 (0.05–0.17)	20.7 (17.2–22.6)	8 (7.2–8.4)	2.9 (2.3–3.1)	6 (5.0–6.5)	0.08 (0.01–0.09)	0.06 (0.02–0.08)

Table A1. *Cont.*

					Mean Physico-Chemical Variables								
Rivers	**Site Codes**	**LIS**	**MIS**	**HIS**	**Water Temperature (°C)**	**Depth (m)**	**Flow Velocity (ms^{-1})**	**Conductivity (μscm^{-1})**	**DO (mgL^{-1})**	**BOD (mgL^{-1})**	**pH**	**Nitrate (mgL^{-1})**	**Phosphate (mgL^{-1})**
Ossiomo	Os2			X	26 (21–27.5)	0.53 (0.45–0.56)	0.26 (0.13–0.28)	23 (21.0–24.0)	6.6 (5.4–7.4)	1.8 (0.9–2.3)	6.2 (5.6–6.7)	0.04 (0.02–0.05)	0.24 (0.06–0.27)
Benin	Be1			X	24.5 (23.1–24.8)	1 (0.4–1.2)	0.13 (0.09–0.16)	24.9 (22.5–25.7)	6.7 (5.0–7.4)	2.9 (1.3–3.7)	6.7 (6.2–6.9)	0.08 (0.02–0.10)	0.08 (0.01–0.09)
Ossiomo	Os1			X	25.9 (24.8–26.7)	0.53 (0.22–0.58)	0.29 (0.12–0.34)	25.6 (21.4–26.2)	6 (5.3–6.2)	2.3 (1.9–2.8)	6.2 (5.4–7.6)	0.05 (0.01–0.07)	0.2 (0.12–0.20)
Owan	Oa			X	24.7 (23.8–25.1)	1.36 (0.62–1.53)	0.34 (0.06–0.42)	29.2 (21.4–30.2)	6.2 (5.1–6.7)	2.1 (1.3–2.9)	6.5 (6.2–6.8)	0.06 (0.01–0.09)	0.69 (0.01–0.87)
Umaluku	Um2			X	26 (21.6–27.3)	0.63 (0.16–0.74)	0.19 (0.11–0.22)	35.5 (26.5–36.0)	5.4 (5.0–6.4)	2.5 (1.8–2.8)	6.8 (5.6–7.2)	1.25 (0.07–1.4)	10.6 (2.5–11.8)
Eriora	Er			X	29.8 (23.8–30.4)	0.75 (0.51–0.78)	0.25 (0.18–0.27)	56.5 (34.0–58.5)	11.3 (5.9–11.8)	9.7 (7.2–11.8)	5.3 (4.7–5.8)	1.45 (0.05–1.57)	0.26 (0.01–0.32)
Umomi	Ui2			X	22.4 (20.0–23.5)	1 (0.40–1.1)	0.22 (0.18–0.26)	62.5 (45.8–63.7)	6.3 (6.2–6.6)	3.5 (2.3–3.9)	6.8 (5.8–7.4)	0.04 (0.01–0.07)	1.3 (1.1–1.4)
Umaluku	Um1			X	25.7 (22.4–26.3)	0.49 (0.21–0.52)	0.22 (0.07–0.26)	70.3 (43.9–71.3)	2.8 (2.2–2.6)	8.8 (7.5–9.7)	5.9 (5.2–6.3)	4.4 (1.2–5.6)	0.34 (0.01–0.52)
Umomi	Ui1			X	22 (20–24.5)	0.99 0.23–1.3)	0.2 (0.10–0.25)	81.9 (72.3–82.6)	5 (4.3–5.4)	3.4 (2.7–3.8)	6.9 (5.8–7.1)	0.03 (0.01–0.04)	1.15 (1.1–1.16)
Benin	Be2			X	24.5 (21–8–26.2)	0.79 (0.52–0.82)	0.19 (0.08–0.25)	198 (187–199)	4 (3.9–4.2)	14.6 (9.5–16.5)	7.2 (6.3–8.0)	0.5 (0.2–0.7)	0.8

Note: LIS = least-impacted sites, MIS = moderately impacted sites, HIS = heavily impacted sites; X means site is either LIS, MIS and HIS.

Table A2. Selected macroinvertebrates metrics for the present study.

Selected Macroinvertebrate Metrics	Corresponding Codes for Selected Metrics	Expected Response of Selected Metrics to Ecosystem Degradation
Abundance measures		
Ephemeroptera family abundance	Eph Abun	Negative
Trichoptera family abundance	Tri Abun	Negative
Ephemeroptera Plecoptera and Trichoptera abundance	EPT Abun	Negative
Ephemeroptera Trichoptera Odonata and Coleoptera abundance	ETOC Abun	Negative
Chironomidae abundance	Chi Abun	Positive
Oligochaeta family abundance	Oli Abun	Positive
Chironomidae + Oligochaeta abundance	Chi + Oli Abun	Positive
Mollusca family abundance	Mol Abun	Positive
Diptera family abundance	Dip Abun	Positive
Decapoda family abundance	Dec Abun	Variable
Mollusca + Diptera family abundance	Mol + Dip Abun	Positive
Mollusca + Decapoda family abundance	Mol + Dec Abun	Variable
Odonata family abundance	Odo Abun	Negative
Coleoptera family abundance	Col Abun	Negative
Hemiptera family abundance	Hem Abun	Negative
Coleoptera + Hemiptera abundance	Col + Hem Abun	Negative
Ephemeroptera Plecoptera and Trichoptera family/Chironomidae abundance	EPT/Chi Abun	Negative
Ephemeroptera Trichoptera Odonata and Coleoptera family/Chironomidae abundance	ETOC/Chi Abun	Negative
Ephemeroptera Trichoptera Odonata and Coleoptera family/Diptera abundance	ETOC/Dip Abun	Negative
Chironomidae/Diptera family abundance	Chi/Dip Abun	Positive
Composition measures		
% Ephemeroptera	%Eph	Negative
% Trichoptera	%Tri	Negative
% Ephemeroptera, Plecoptera and Trichoptera	%EPT	Negative
% Ephemeroptera, Trichoptera, Odonata and Coleoptera	%ETOC	Negative
% Chironomidae	%Chi	Positive
% Oligochaeta	%Oli	Positive
%Chironomidae+Oligochaeta	%Chi + Oli	Positive
% Mollusca	%Mol	Positive
% Diptera	%Dip	Positive
% Decapoda	%Dec	Variable
%Mollusca+Decapoda	%Mol + Dec	Variable
%Mollusca+Diptera	%Mol + Dip	Positive
% Coleoptera	%Col	Negative
% Hemiptera	%Hem	Negative

Table A2. *Cont.*

Selected Macroinvertebrate Metrics	Corresponding Codes for Selected Metrics	Expected Response of Selected Metrics to Ecosystem Degradation
% Odonata	%Odo	Negative
% Coleoptera + Hemiptera	%Col + Hem	Negative
Richness measures		
Ephemeroptera richness	Eph Rich	Negative
Trichoptera richness	Tri Rich	Negative
Ephemeroptera, Plecoptera and Trichoptera richness	EPT Rich	Negative
Ephemeroptera, Trichoptera, Odonata and Coleoptera richness	ETOC Rich	Negative
Mollusca richness	Mol Rich	Positive
Diptera richness	Dip Rich	Increase
Chironomidae richness	Chi Rich	Positive
Oligochaeta richness	Oli Rich	Positive
Chironomidae + Oligochaeta richness	Chi + Oli Rich	Positive
Coleoptera richness	Col Rich	Negative
Hemiptera richness	Hem Rich	Negative
Coleoptera + Hemiptera richness	Col + Hem Rich	Negative
Odonata richness	Odo Rich	Negative
Decapoda richness	Dec Rich	Variable
Diversity measures		
Shannon–Wiener diversity index (H)	Sha Ind	Negative
Margalef index (Taxa diversity index)	Mar Ind	Negative
Evenness index (e^H/S)	Eve Ind	Negative
Simpson diversity (1–D)	Sim Div	Negative
Traits measures		
Logarithm of relative abundance of large (>20–40 mm)	Log Lar	Negative
Logarithm of relative abundance of hardshell	Log HaS	Negative
Logarithm of relative abundance of predator	Log Pre	Positive
Logarithm of relative abundance of nymph	Log Nym	Negative
Logarithm of relative abundance of pupa aquatic stage	Log Pup	Positive

Table A3. Confirmation of selected forested riverine system macroinvertebrate metrics sensitivity to urban pollution. **Note: Sensitivity of a metric is confirmed if its *p*-value is <0.05. √ = sensitivity confirmed, X = sensitivity not confirmed.**

Metrics	Mann–Whitney Test	*p*-Value	Metric Sensitivity Status
Abundance measures			
Tri Abun	750	0.0025	√
Col Abun	919	0.087	X
EPT/Chi Abun	468	5.35×10^{-7}	√

Table A3. *Cont.*

Metrics	Mann–Whitney Test	*p*-Value	Metric Sensitivity Status
	Composition measures		
%EPT	968	0.18	X
%Tri	967	0.16	X
%ETOC	992	0.24	X
%Odo	763	0.0044	√
%Mol+Dip	401	3.81×10^{-8}	√
%Chi	296	3.61×10^{-10}	√
%Chi+Oli	388	2.16×10^{-8}	√
%Dip	441	1.93×10^{-7}	√
	Richness measures		
ETOC Rich	959	0.16	X
Col Rich	663	0.000305	√
Hem Rich	721	0.0013	√
Col+Hem Rich	602	5.17×10^{-5}	√
Odo Rich	923	0.090	X
	Diversity measures		
Sha Div	764	0.0045	√
Mar Ind	608	6.71×10^{-5}	√
Sim Div	663	0.00040	√
	Trait attributes measures		
LogPup	993	0.025	√

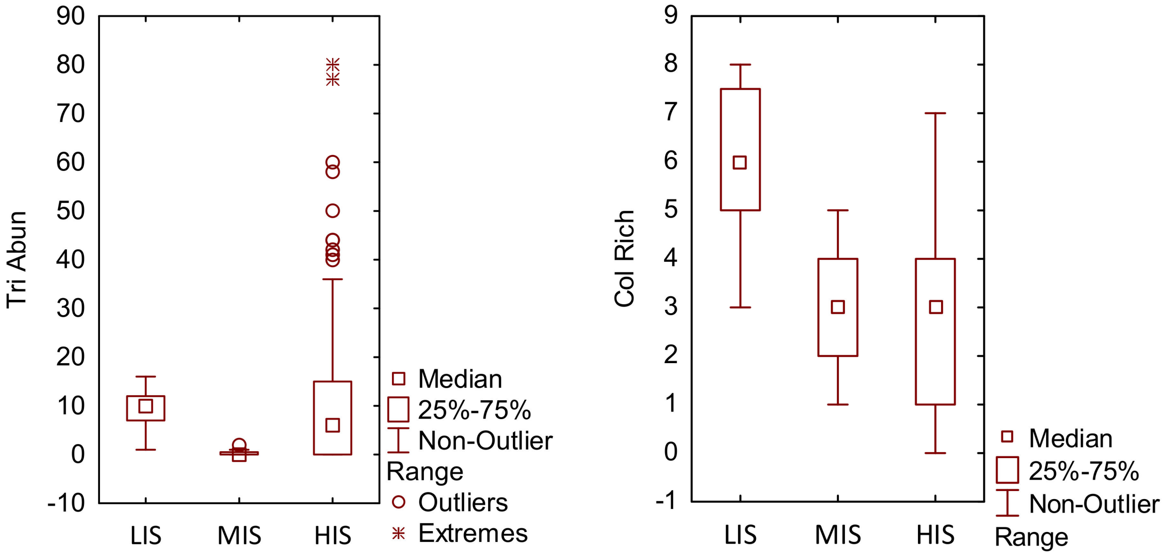

Figure A1. *Cont.*

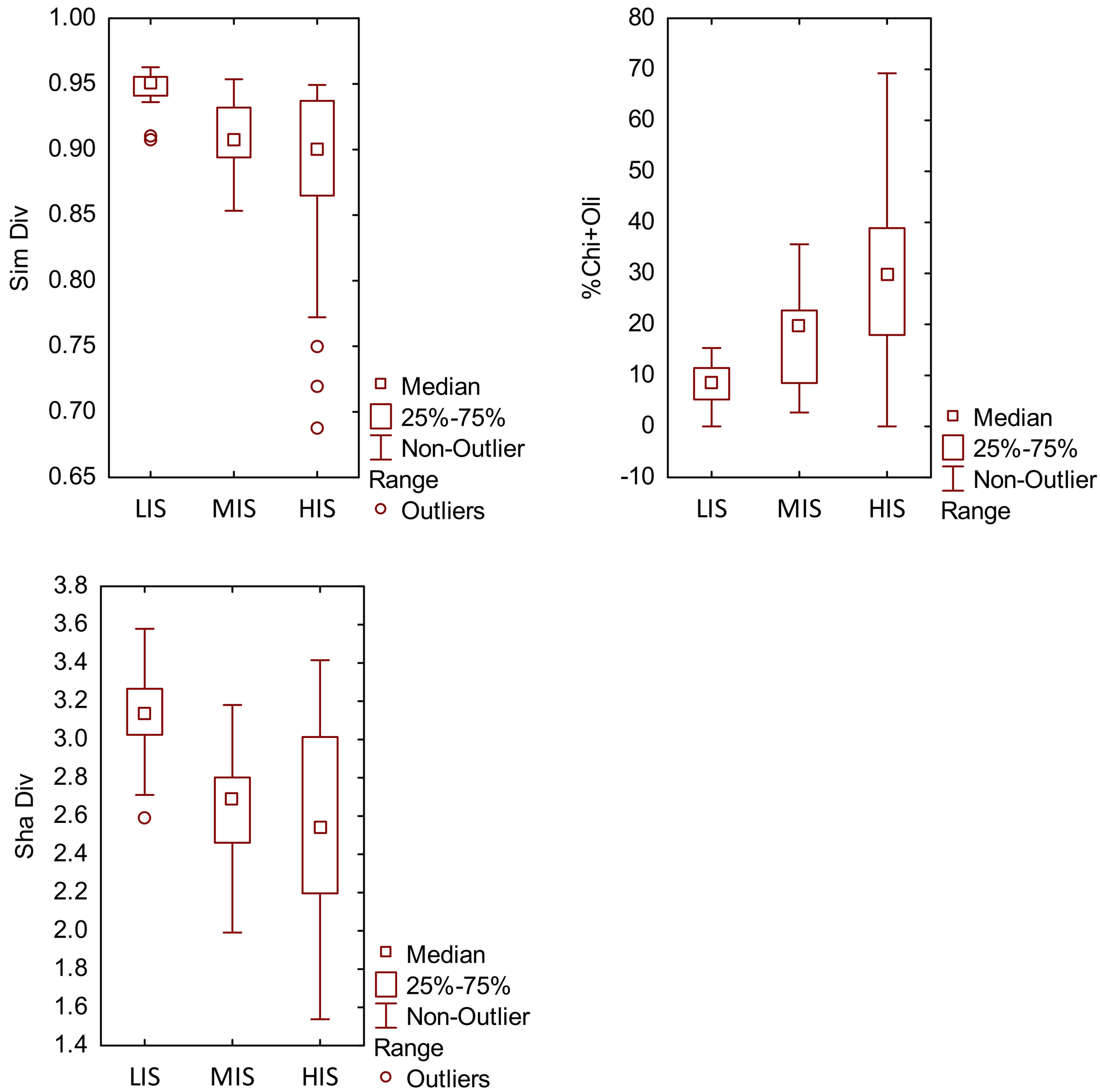

Figure A1. Box and whisker plots showing metric sensitivity between least-impacted sites (LIS), moderately impacted sites (MIS), and highly impacted sites (HIS).

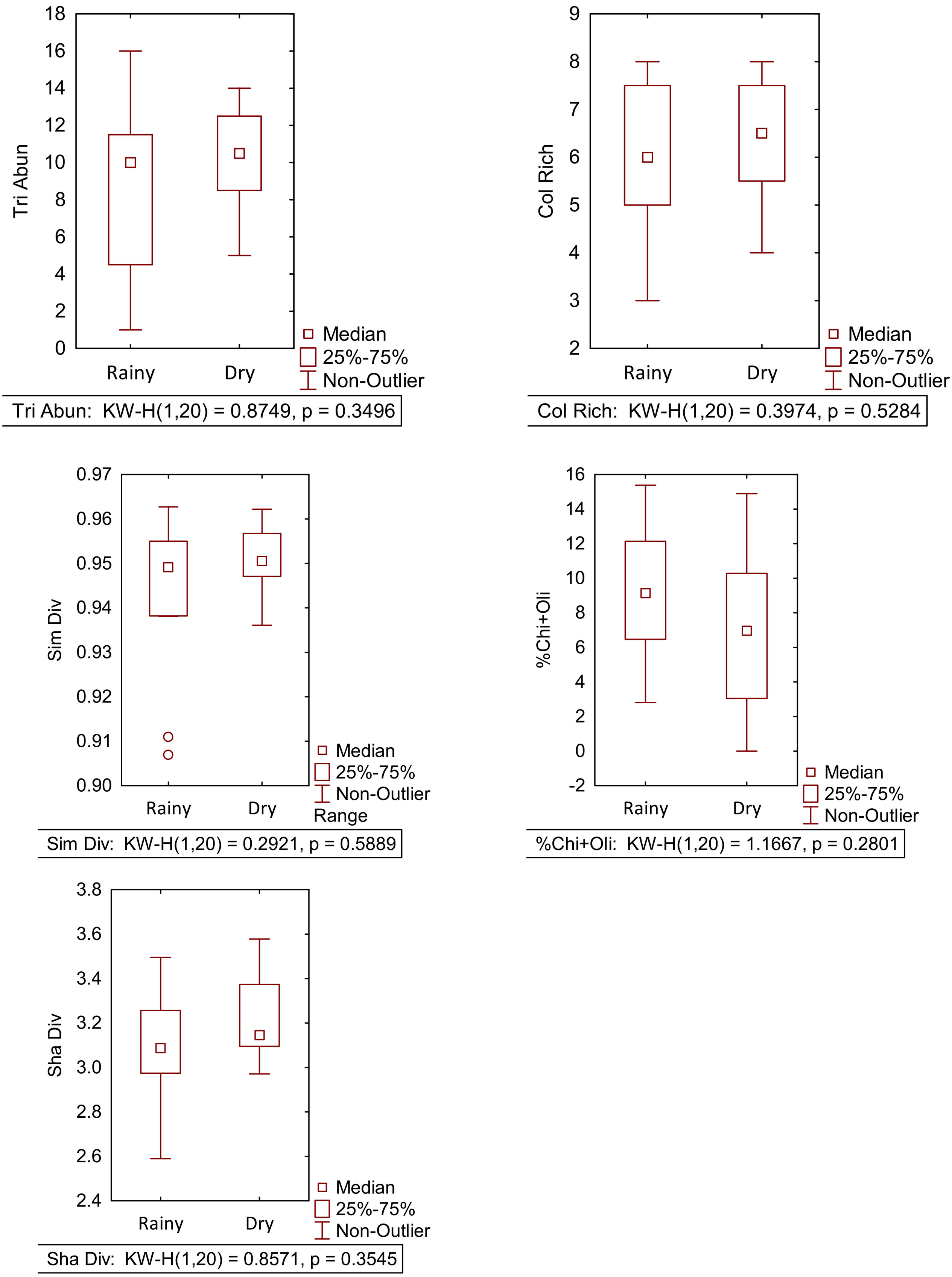

Figure A2. Box and whisker plots showing metric seasonality.

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