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# Diatom-based Index: A tool for Assessing Water Quality in A Southeast Asian Tropical River Basin

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## ABSTRACT

Diatoms are key components of freshwater ecosystems, serving as primary producers and indicators of ecosystem health. Twenty-eight rivers and streams within a Southeast Asian River basin were sampled for diatoms and physicochemical conditions. Diatoms and local standards of physicochemical conditions were analyzed using canonical correspondence analysis. A diatom-based index was developed using pollution values of taxon (PVT) generated using physicochemical conditions and local limits. The CCA revealed that some diatoms responded to local standards, reflecting environmental conditions. Axis 1 is characterized by nutrient related variables explaining 33.04% of the species-physicochemical relationship while Axis 2, characterized by chemical gradients, explains 21.26%. PVT values profiled diatoms in terms of tolerance. Higher PVT are indicative of higher tolerance for disturbance while lower PVT indicate sensitivity. *Achnanthidium, Fragilaria, Gomphoneis, Gomphonema, Luticola, Navicula, Nitzschia, Pinnularia* and *Surirella* had the highest PVT values indicating high tolerance to disturbance. These taxa occupy wide ranges of environmental conditions. Genera like *Sellaphora* and *Pleurosira* had the lowest PVT values and are found in narrow niches. Majority of the areas are moderately disturbed based on the developed index. Moderate and low disturbance areas are recommended for prioritization in conservation efforts since they may still be reversible in terms of disturbance levels. Low disturbance areas may serve as reference sites for good water quality and ecological status of the river basin. The development of a diatom-based index encourages the use of diatoms for routine water quality and ecological assessments in local Southeast Asian River basins.

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## INTRODUCTION

Actions to monitor, restore, protect, and utilize water ecosystems require adequate understanding and knowledge of the freshwater body's biological community structure and water quality (Cartwright & Miller, 2021; Sinco et al., 2014). As such, biological components alongside physicochemical parameters are used to assess water quality and give insights to ecological status (Maznah & Omar, 2010; Oeding & Taffs, 2015). Biological components such as diatoms are great tools to utilize to reach water quality assessment and monitoring goals. Diatoms are algae that have quick generation times and are sensitive to environmental changes. This allows them to become indicators of pollution in freshwater bodies (Nautiyal et al., 2015) and be used for freshwater biomonitoring (Srivastava et al., 2016).

Diatom-based indices were developed to utilize the diatom's generally cosmopolitan distribution and robust relationship to nutrient and environmental variables (Bere & Tundisi, 2011;

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Dell'uomo & Torrisi, 2011). However, indices developed in a different geographical setting may not necessarily be applicable to other settings as techniques that depend on pollution-tolerance values are often region specific (Resh, 2007) and species' autoecological parameters between regions show variation (Álvarez-Blanco et al., 2011). The species–environment relationships originally assessed could be different in other geographic areas (Álvarez-Blanco et al., 2011; Dalu et al., 2016), expressing concern on which indices best reflect water quality and ecological status of freshwater systems especially if the indices were developed in vastly different settings. These challenges can be addressed by developing an index that reflects autoecologies of local diatoms rather than of those developed from a different locality. Additionally, local standards for water quality can be integrated into the index to ensure that the index reflects the standards and definitions set by local authorities.

Southeast Asian River basins share similar climate timings (Hasson et al., 2016) which results to similar terrain and geography. Similarities also extend to stressors such as agricultural practices, utilization of resources, and similar levels of environmental policies. The study area, the Tagoloan River Basin is the 13th largest river basin in the Philippines, a Southeast Asian tropical country. Freshwater ecosystems within the basin are considered vulnerable (Li et al., 2010), especially to human disturbances such as agricultural and industrial water discharges, pollution, urbanization, and other anthropogenic influences. Thus, legislation and guidelines across the globe and various regions were accordingly developed for routine water quality and freshwater resources or ecosystems such as Europe Water Framework Directive in Europe (European Community, 2000), Clean Water Act in the United States of America, and Strategic priorities by the Association of Southeast Asian Nations (*ASEAN Integrated Water Resource Management (IWRM)*, 2022). In the Philippines, the Philippine Republic Act 9275 (Clean Water Act of 2004) and Department Administrative Order 2016-08 (DENR EMB, 2016) are all set towards monitoring, assessing, conservation, and protection of natural resources. In line with this, the development of a local index will account for the local genera-environment relationship and local standards, answering concerns of applicability of indices developed in a geographically distant and different region as well as fostering more understanding of biological and environmental relationships of areas being monitored. This study uses the diatom community as a tool for water quality assessments in rivers and streams of the Tagoloan River Basin, in combination with physical and chemical conditions. Overall, this study enhances our knowledge of using diatom-based assessments for routine water quality and ecological evaluations in a local Southeast Asian River basin.

## METHODOLOGY

Rivers and streams in twenty-eight areas (28) were selected to represent the Tagoloan River Basin (Figure 1). To achieve a robust data set, each river or stream had nine (9) sampling points respectively. The drainage area of the river basin is estimated to be 1,704 km$^2$ (Paringit et al., 2015). Coordinates and elevation data was taken using GARMIN eTrex® 10 device. Average elevation for each area were calculated and quartiles method was used to classify areas into upstream, midstream, and downstream. One-time sampling was employed throughout a year for the collection of water quality parameters and diatom data since there is no wide variation in terms of seasonality or weather conditions throughout the year.

Collection of water samples and all laboratory methods for analysis are shown in table 1 and were based on the methods in the Standard Methods for the Examination of Water and Wastewater 23rd Edition (Baird et al., 2017).

Epilithic diatoms were collected by brushing cobble sized rocks using firm-bristled brush to dislodge the diatoms from the rock substrate. The dislodged diatoms were transferred to amber bottles with 5% buffered formalin as preservative. Cleaning of samples was conducted using

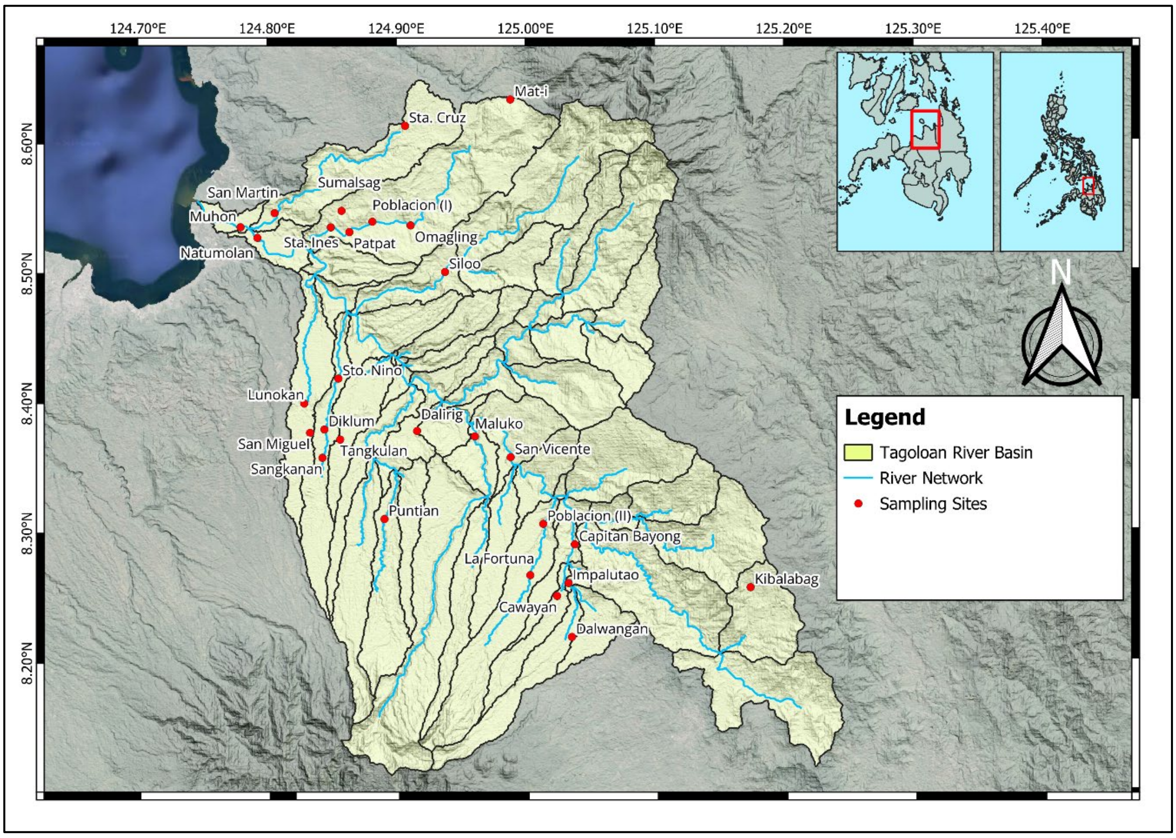

**Fig. 1.** Map of the Tagoloan River Basin

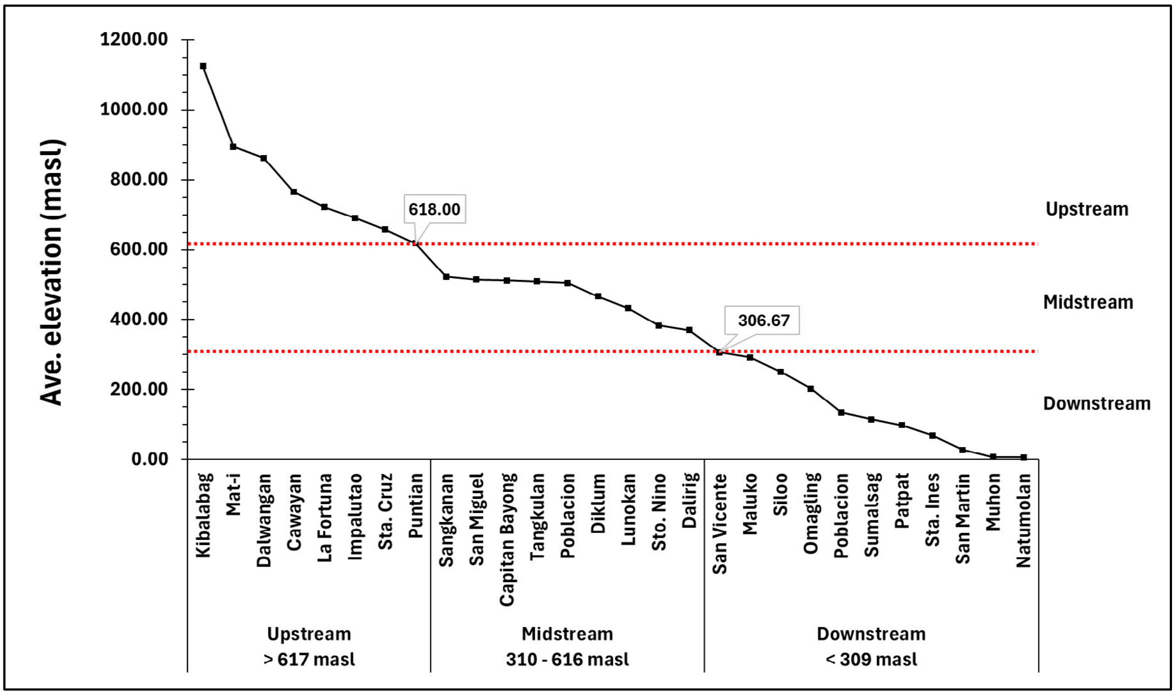

**Fig. 2.** Mean elevation of rivers and streams in sampling areas in the Tagoloan River Basin with their corresponding elevation classification. Red target lines delineate elevation classifications.

**Table 1.** Water quality parameters and analysis method/instrument used in the study.

| Parameter | Analysis method/Instrument |
|---|---|
| Temperature (°C)<br>pH<br>Total Dissolved Solids<br>Dissolved Oxygen | HACH limnology model AL-36DT multiparameter probe |
| Conductivity | WTW Cond 3210 Set 1 incl. TetraCon® 325 |
| Nitrite<br>Nitrate<br>Iron<br>Phosphate<br>Biological Oxygen Demand ($BOD_5$)<br>Ammonium<br>Hardness<br>Turbidity | Spectrophotometric Tests (Merck KGaA, Darmstadt, Germany) |
| Total Suspended Solids | Gravimetric method |

the hot hydrogen peroxide oxidation method (Taylor & Cocquyt, 2016) and frustules were fixed on permanent mounts with Naphrax resin (Brunel Microscopes Ltd, UK). The frustules were observed and counted using a light microscope at a 1000× magnification. Identification of diatoms were limited to the genera level and were based on Taylor et al. (2007), Taylor & Cocquyt (2016), Lange-Bertalot et al. (2017), and Spaulding et al. (2021). General level identification was implemented in order to alleviate the major challenges of taxonomic clarity which is common in developing countries with less taxonomic experts and minimal studies on ecological requirements of local diatom species (Bere, 2016).

Canonical correspondence analysis was done to explore diatom and Physicochemical conditions. Analysis was performed using PAST 4.03 software (Hammer et al., 2001). Pollution index (*PI*) based on the methods and formula proposed by (Jiang & Shen, 2003) and (Jiang, 2006) were followed, where *C* is the mean of the physicochemical variable, and *CL* is the limiting value based on local standards, in this case, Class A waters described in the Department Administrative Order 2016-08 (DENR EMB, 2016). Each area will have a *PI* value for its rivers and streams.

$$PI = \sum_{i=1}^{n} \frac{C}{CL}$$

Pollution values for the taxon (PVT) were calculated using the following formula where *n* is the number of measured Physicochemical variables, *ln* is the natural logarithm, *N* is the number of sites and *i* is the presence of each genera in a particular sampling area.

$$PVT = \frac{\sum_{i=1}^{n} \left( \frac{lnPI}{n} \right) i}{N}$$

The last step was to calculate for the pollution value of the diatom community for each area (Astrid Sinco (5)-Philippine Diatom Index for the Tagoloan River Basin - A5-PDI-TRB). The formula below is based on Castro-Roa & Pinilla-Agudelo (2014). Data was transformed using a percentage transformation with 100% as the maximum or highest value among the A5-PDI-TRB. The results were then subtracted from 100 to obtain a score that is directly proportional to the area's status. Quartiles technique was used to classify the different scores into their degree of disturbance.

$$A5-PDI-TRB=\frac{\sum_{i=1}^{n}(PVT)i}{n_s}$$

## RESULTS AND DISCUSSION

Mean physicochemical conditions showed that several areas had measurements that are outside the recommended limits based on the local DAO 2016-08 standard for Class A waters for some parameters (Table 2 and 3). These physicochemical conditions are phosphate, nitrate, pH, TSS, and temperature which are associated with anthropogenic origins. Nitrate and Phosphate input to freshwaters reflect legacies of current and past applications of fertilizers and manure, and act as stimulators of phytoplankton growth resulting in eutrophication (Bijay-Singh & Craswell, 2021) and are also indicative of possible wastewater contamination from nearby settlements (Manning, 2008). Seasonal fluctuations and natural lotic aquatic system dynamics may have attributed to the variation of pH (Husain & Kumar, 2022), however acidification, salinization, and alkalization can still enter or occur in a stream through human disturbance (Wu et al., 2021). Concentrations of total suspended solids in aquatic systems are affected by not just by seasonality but also joined with anthropogenic factors such mining, construction, shipping, sand quarrying, etc. (Ghosh et al., 2023). The elevated measurements are most likely associated with the presence of these influences and the natural factors like rainfall duration, intensity, and geology of the area. Lastly, temperature readings that were out of standard range were considered negligible as collection of water samples were done in early morning which were expected to have lower temperatures. Areas that are of high elevation also exhibited lower mean temperatures which is due to the typically cooler weather conditions associated with the areas. Physicochemical measurements are showing hints on a possible anthropogenic associated influence towards the sampled rivers and streams.

Diatoms are considered as good indicators of the environmental disturbance and integrity of freshwater ecosystems because they are common in most streams and they are at the base of the food chain (Sinco & Tampus, 2020). Furthermore, diatoms are proven to be able to discriminate low or high nutrients such as dissolved phosphate (Sinco & Metillo, 2010).

Ordination of data through canonical correspondence analysis was able to reveal diatom and Physicochemical variable relationships across different gradients (Figure 3). Axis 1 explains 33.04% of the variance and is characterized by a nutrient-related variables, suspended particles, and mineralization gradient; Nitrate, nitrite, phosphate for Nutrient-related variables, TSS and Turbidity for suspended particles, and hardness, TDS, and conductivity for mineralization. Axis 2 explains 21.26% of the variance and is characterized by chemical gradients; DO, pH, $BOD^5$, Temperature, iron, and ammonium.

The biplot in Figure 3 show that there are diatoms that exhibit a relationship towards specific Physicochemical variables. *Cymbella* (Cymb), *Gyrosigma* (Gyro), *Pleurosira* (Pleura), *Pinnularia* (Pinn) and *Surirella* (Suri) appear to be associated with lower values of axis 1 variables. The association of these taxa corresponds to known autoecologies. For example, the association of *Cymbella* towards low-nutrient waters is supported by known preferences of several of its species which are oligotrophic or low nutrient waters (Taylor et al., 2007; Taylor & Cocquyt, 2016). In contrast, some genera like *Melosira*, *Luticola*, and *Planothidium* are positioned towards higher values on the axis 1. This indicates that these taxa favor higher values of Physicochemical variables that characterize axis 1. *Melosira* are abundant in eutrophic, occasionally slightly brackish waters (Taylor et al., 2007); some species of Luticola are known to tolerate heavily polluted waters (Taylor et al., 2007); and lastly some species of *Planothidium*

**Table 2.** Mean physicochemical conditions (Phosphate, Nitrate, Turbidity, Nitrite, Ammonium, Iron, pH, and Temperature) of sampled rivers and streams. An asterisk (*) indicates a local standard value or range present and red text indicate that the values are above or below the standard value or out of range.

| Sampling Area | Parameter | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Phosphate (mg/L) *Standard value = < 0.05 | Nitrate (mg/L) *Standard value = 7.00 | Turbidity | Nitrite (mg/L) | Ammonium (mg/L) | Iron (mg/L) *Standard value = 1.00 | pH *Standard range = 6.50 – 8.50 | Temperature (°C) *Standard range = 26.00 – 30.00 |
| **Kibalabag** | 0.01 ± 0.00 | 6.33 ± 3.61 | 1.00 ± 1.94 | 0.00 ± 0.00 | 0.073 ± 0.04 | 0.41 ± 0.06 | 8.37 ± 0.30 | 21.44 ± 0.55 |
| **Mat-i** | 0.05 ± 0.03 | 1.67 ± 0.50 | 10.00 ± 0.00 | 0.01 ± 0.00 | 0.71 ± 0.56 | 0.15 ± 0.07 | 7.36 ± 0.25 | 21.57 ± 0.20 |
| **Dalwangan** | 0.01 ± 0.00 | 4.22 ± 2.95 | 1.48 ± 1.77 | 0.01 ± 0.01 | 0.04 ± 0.04 | 0.43 ± 0.08 | 7.7 ± 0.32 | 24.00 ± 0.46 |
| **Cawayan** | 0.01 ± 0.01 | 5.51 ± 2.74 | 3.22 ± 1.20 | 0.02 ± 0.00 | 0.04 ± 0.04 | 0.14 ± 0.03 | 7.72 ± 0.05 | 26.76 ± 0.63 |
| **La Fortuna** | 0.04 ± 0.08 | 5.56 ± 2.13 | 0.67 ± 0.5 | 0.02 ± 0.00 | 0.01 ± 0.00 | 0.08 ± 0.03 | 7.94 ± 0.08 | 26.31 ± 0.25 |
| **Impalutao** | 0.01 ± 0.01 | 3.11 ± 1.69 | 1.00 ± 0.00 | 0.02 ± 0.01 | 0.02 ± 0.02 | 0.14 ± 0.09 | 7.76 ± 0.41 | 24.03 ± 0.85 |
| **Sta. Cruz** | 0.03 ± 0.02 | 8.00 ± 3.12 | 8.33 ± 1.32 | 0.06 ± 0.06 | 0.17 ± 0.11 | 0.40 ± 0.10 | 7.75 ± 0.03 | 23.64 ± 0.26 |
| **Puntian** | 0.01 ± 0.00 | 7.44 ± 3.13 | 8.00 ± 1.73 | 0.01 ± 0.00 | 0.21 ± 0.02 | 0.03 ± 0.02 | 5.73 ± 0.02 | 22.88 ± 0.51 |
| **Sangkanan** | 0.05 ± 0.01 | 8.00 ± 2.83 | 5.67 ± 0.50 | 0.02 ± 0.00 | 0.16 ± 0.07 | 0.01 ± 0.05 | 7.73 ± 0.04 | 23.58 ± 0.26 |
| **San Miguel** | 0.04 ± 0.01 | 32.44 ± 1.33 | 11.00 ± 4.77 | 0.08 ± 0.03 | 0.17 ± 0.07 | 0.11 ± 0.09 | 7.16 ± 0.07 | 25.53 ± 0.24 |
| **Capitan Bayong** | 0.01 ± 0.00 | 9.00 ± 1.00 | 0.78 ± 0.44 | 0.02 ± 0.00 | 0.03 ± 0.02 | 0.05 ± 0.01 | 8.37 ± 0.04 | 23.26 ± 0.61 |
| **Tangkulan** | 0.07 ± 0.06 | 4.11 ± 1.76 | 14.00 ± 1.41 | 0.01 ± 0.00 | 0.16 ± 0.09 | 0.29 ± 0.01 | 7.65 ± 0.09 | 25.72 ± 0.39 |
| **Poblacion (I)** | 0.02 ± 0.01 | 3.78 ± 2.54 | 1.00 ± 0.00 | 0.02 ± 0.00 | 0.02 ± 0.03 | 0.03 ± 0.03 | 8.50 ± 0.03 | 25.13 ± 0.55 |
| **Diklum** | 8.34 ± 5.88 | 106.44 ± 46.87 | 43.89 ± 6.97 | 18.44 ± 10.50 | 0.67 ± 0.16 | 0.18 ± 0.03 | 6.97 ± 0.09 | 26.12 ± 0.41 |
| **Lunokan** | 0.43 ± 0.07 | 15.78 ± 7.55 | 2.11 ± 1.27 | 0.07 ± 0.00 | 1.41 ± 1.40 | 0.19 ± 0.01 | 8.07 ± 0.14 | 26.61 ± 0.46 |
| **Sto. Nino** | 0.03 ± 0.01 | 8.11 ± 3.55 | 3.22 ± 0.97 | 0.02 ± 0.00 | 0.13 ± 0.05 | 0.04 ± 0.05 | 8.08 ± 0.06 | 24.09 ± 0.09 |
| **Dalirig** | 0.11 ± 0.09 | 32.11 ± 21.45 | 1.00 ± 0.00 | 0.00 ± 0.00 | 0.13 ± 0.09 | 0.3 ± 0.18 | 8.06 ± 0.16 | 24.22 ± 0.19 |
| **San Vicente** | 0.02 ± 0.00 | 10.00 ± 2.24 | 3.22 ± 1.20 | 0.03 ± 0.00 | 0.23 ± 0.03 | 0.04 ± 0.02 | 5.76 ± 0.02 | 30.06 ± 3.68 |
| **Maluko** | 0.24 ± 0.07 | 12.44 ± 6.67 | 1.11 ± 0.33 | 0.04 ± 0.01 | 0.17 ± 0.25 | 0.22 ± 0.10 | 7.68 ± 0.21 | 23.34 ± 1.65 |
| **Silo-o** | 0.07 ± 0.01 | 36.36 ± 5.8 | 1.78 ± 2.28 | 0.01 ± 0.00 | 0.30 ± 0.47 | 0.1 ± 0.04 | 8.41 ± 0.07 | 24.40 ± 1.39 |
| **Omagling** | 0.02 ± 0.00 | 33.68 ± 3.9 | 0.22 ± 0.44 | 0.01 ± 0.00 | 0.57 ± 0.85 | 0.13 ± 0.05 | 8.63 ± 0.04 | 27.21 ± 0.53 |
| **Poblacion (II)** | 0.03 ± 0.02 | 19.89 ± 15.28 | 1.56 ± 1.01 | 7.56 ± 6.52 | 0.17 ± 0.18 | 0.04 ± 0.02 | 7.84 ± 0.17 | 24.60 ± 0.09 |
| **Sumalsag** | 0.03 ± 0.02 | 26.67 ± 6.56 | 1.00 ± 0.00 | 4.67 ± 2.00 | 0.08 ± 0.06 | 0.01 ± 0.00 | 7.97 ± 0.15 | 27.47 ± 0.55 |
| **Patpat** | 0.06 ± 0.03 | 37.00 ± 17.20 | 7.44 ± 1.67 | 1.00 ± 0.00 | 0.5 ± 0.27 | 0.04 ± 0.01 | 7.76 ± 0.22 | 26.63 ± 0.41 |
| **Sta. Ines** | 0.09 ± 0.03 | 47.44 ± 33.56 | 7.89 ± 1.69 | 0.94 ± 0.17 | 0.19 ± 0.31 | 0.04 ± 0.00 | 7.68 ± 0.36 | 24.54 ± 0.39 |
| **San Martin** | 0.20 ± 0.23 | 27.33 ± 18.38 | 8.00 ± 0.87 | 0.02 ± 0.00 | 0.25 ± 0.03 | 0.29 ± 0.10 | 8.79 ± 0.03 | 28.59 ± 0.11 |
| **Muhon** | 0.06 ± 0.02 | 37.13 ± 7.19 | 5.33 ± 2.18 | 0.01 ± 0.00 | 0.09 ± 0.05 | 0.66 ± 0.24 | 8.83 ± 0.11 | 29.91 ± 0.35 |
| **Natumolan** | 0.04 ± 0.02 | 33.06 ± 3.22 | 1.56 ± 0.53 | 0.01 ± 0.00 | 0.03 ± 0.03 | 0.23 ± 0.16 | 9.11 ± 0.33 | 29.53 ± 0.39 |

**Table 3.** Mean physicochemical conditions (TDS, Conductivity, DO, TSS, Hardness, and $BOD^5$) of sampled rivers and streams. An asterisk (*) indicates a local standard value or range present and red text indicate that the values are above or below the standard value or out of range.

| Sampling Area | Parameter | | | | | |
|---|---|---|---|---|---|---|
| | Total Dissolved Solids (mg/L) | Conductivity (TDS/0.67) | Dissolved Oxygen (mg/L) *Standard value (minimum) = 5.00 | Total Suspended Solids (mg/L) *Standard value = 50.00 | Hardness (CaCO3 mg/L) | $BOD^5$ (mg/L) *Standard value = 3.00 |
| **Kibalabag** | 205.44 ± 28.77 | 205.56 ± 28.71 | 7.01 ± 0.41 | 262.01 ± 259.20 | 137.78 ± 32.32 | 2.00 ± 1.41 |
| **Mat-i** | 41.33 ± 13.86 | 36.90 ± 3.57 | 7.26 ± 0.05 | 98.81 ± 115.04 | 20.00 ± 0.00 | 0.78 ± 0.67 |
| **Dalwangan** | 168.11 ± 0.93 | 169.17 ± 1.70 | 6.65 ± 0.15 | 41.61 ± 70.86 | 84.44 ± 13.33 | 1.00 ± 1.22 |
| **Cawayan** | 61.11 ± 1.54 | 58.51 ± 1.68 | 7.31 ± 0.19 | 146.68 ± 140.57 | 30.44 ± 11.4 | 1.67 ± 1.12 |
| **La Fortuna** | 52.44 ± 2.51 | 50.24 ± 1.73 | 7.31 ± 0.04 | 29.80 ± 76.10 | 24.7 ± 9.01 | 1.11 ± 1.45 |
| **Impalutao** | 114.67 ± 14.16 | 109.70 ± 13.27 | 7.19 ± 0.49 | 45.48 ± 45.83 | 43.7 ± 12.42 | 0.44 ± 1.01 |
| **Sta. Cruz** | 48.11 ± 2.26 | 45.88 ± 1.07 | 7.61 ± 0.09 | 69.87 ± 99.20 | 20.00 ± 0.00 | 1.56 ± 1.51 |
| **Puntian** | 103.67 ± 0.50 | 99.09 ± 0.86 | 7.46 ± 0.09 | 18.49 ± 25.49 | 60.00 ± 0.00 | 1.38 ± 1.95 |
| **Sangkanan** | 65.78 ± 3.73 | 64.27 ± 1.49 | 7.51 ± 0.04 | 127.10 ± 100.17 | 34.2 ± 0.00 | 1.56 ± 1.67 |
| **San Miguel** | 116.11 ± 3.92 | 111.23 ± 3.70 | 6.27 ± 0.18 | 478.11 ± 373.57 | 66.67 ± 10.00 | 1.22 ± 1.39 |
| **Capitan Bayong** | 150.44 ± 18.59 | 137.79 ± 0.98 | 7.92 ± 0.07 | 92.61 ± 97.66 | 55.10 ± 7.54 | 0.98 ± 1.47 |
| **Tangkulan** | 82.67 ± 12.13 | 123.38 ± 18.11 | 7.15 ± 0.08 | 45.42 ± 28.91 | 36.10 ± 5.70 | 1.00 ± 0.71 |
| **Poblacion (I)** | 134.69 ± 4.69 | 129.23 ± 4.10 | 7.79 ± 0.07 | 17.27 ± 37.49 | 53.20 ± 5.70 | 0.58 ± 1.73 |
| **Diklum** | 63.22 ± 8.38 | 94.36 ± 12.50 | 7.05 ± 0.04 | 37.60 ± 6.93 | 28.50 ± 8.55 | 1.89 ± 1.27 |
| **Lunokan** | 250.89 ± 7.96 | 374.46 ± 11.88 | 7.01 ± 0.08 | 38.29 ± 41.03 | 100.7 ± 13.37 | 1.56 ± 2.55 |
| **Sto. Nino** | 140.33 ± 1.87 | 135.28 ± 2.61 | 7.53 ± 0.06 | 350.16 ± 306.52 | 51.30 ± 0.00 | 0.33 ± 0.55 |
| **Dalirig** | 301.00 ± 16.96 | 449.25 ± 25.31 | 7.54 ± 0.08 | 46.48 ± 42.80 | 127.3 ± 19.33 | 0.44 ± 1.01 |
| **San Vicente** | 166.11 ± 1.27 | 159.87 ± 1.07 | 7.49 ± 0.13 | 19.61 ± 27.02 | 80.00 ± 0.00 | 2.38 ± 2.12 |
| **Maluko** | 140.78 ± 9.46 | 210.12 ± 14.12 | 7.93 ± 0.08 | 113.04 ± 311.17 | 45.60 ± 8.55 | 1.78 ± 1.48 |
| **Silo-o** | 176.89 ± 22.25 | 176.34 ± 9.16 | 7.76 ± 0.14 | 8.93 ± 2.36 | 68.40± 8.55 | 2.89 ± 3.06 |
| **Omagling** | 175.22 ± 9.64 | 166.62 ± 8.52 | 7.54 ± 0.09 | 7.00 ± 2.87 | 68.40 ± 1.51 | 2.02 ± 2.29 |
| **Poblacion (II)** | 506.67 ± 1.00 | 756.22 ± 1.49 | 7.42 ± 0.01 | 55.82 ± 36.88 | 117.80 ± 41.40 | 1.78 ± 1.86 |
| **Sumalsag** | 513.33 ± 17.72 | 766.17 ± 26.45 | 7.41 ± 0.12 | 38.55 ± 22.89 | 169.10 ± 15.87 | 1.00 ± 2.83 |
| **Patpat** | 170.00 ± 0.71 | 253.73 ± 1.06 | 7.39 ± 0.13 | 13.32 ± 5.73 | 74.10 ± 8.55 | 2.11 ± 1.62 |
| **Sta. Ines** | 180.89 ± 3.82 | 269.98 ± 5.71 | 7.75 ± 0.07 | 15.99 ± 3.70 | 85.50 ± 14.81 | 2.67 ± 2.65 |
| **San Martin** | 192.00 ± 1.22 | 185.49 ± 1.74 | 7.82 ± 0.06 | 167.30 ± 185.76 | 74.10 ± 8.55 | 1.67 ± 1.41 |
| **Muhon** | 214.67 ± 6.91 | 194.18 ± 33.36 | 8.76 ± 1.26 | 68.06 ± 28.76 | 85.50 ± 8.55 | 1.44 ± 1.24 |
| **Natumolan** | 197.89 ± 2.85 | 190.41 ± 2.29 | 9.55 ± 1.07 | 23.35 ± 30.68 | 68.40 ± 1.51 | 0.56 ± 1.01 |

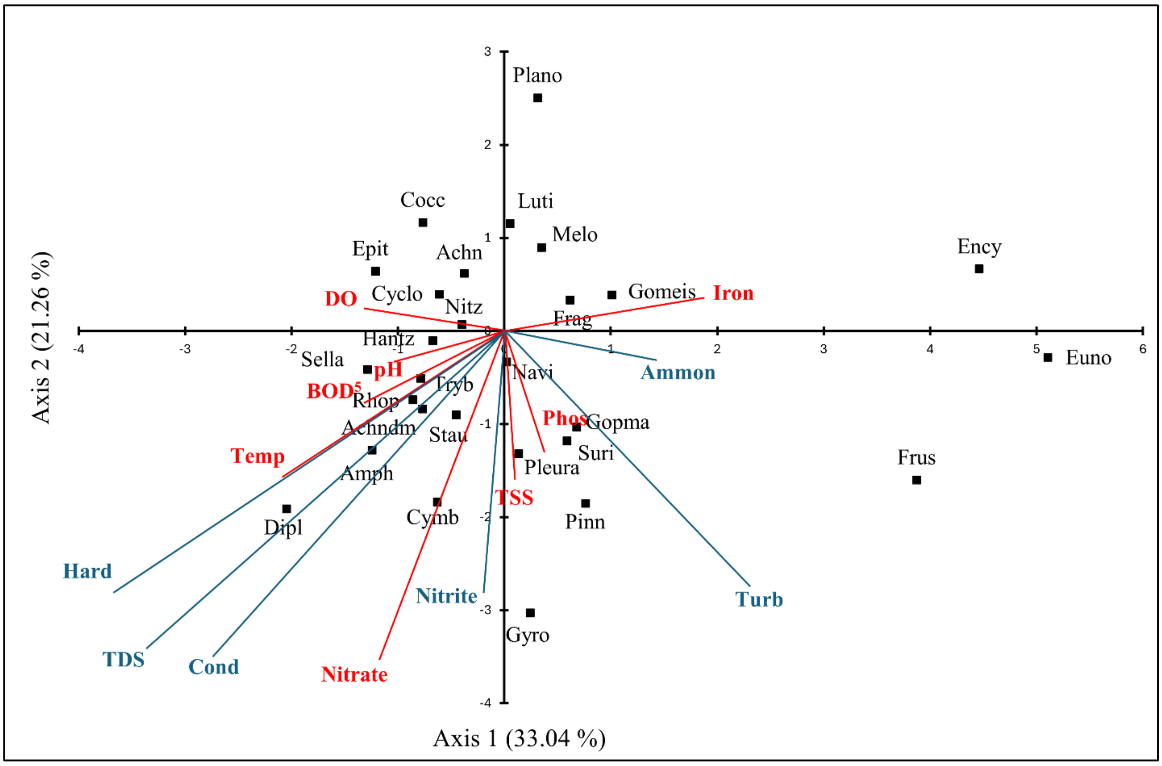

**Fig. 3.** Canonical correspondence analysis biplot of Physicochemical variables and diatoms. Red vectors are highlighted to represent parameters with upper limits and range set by local authorities. Achn = *Achnanthes*, Achndm = *Achnanthidium*, Amph = *Amphora*, Cocc = *Cocconeis*, Cyclo = *Cyclotella*, Cymb = *Cymbella*, Dipl = *Diploneis*, Ency = *Encyonema*, Epit = *Epithemia*, Euno = *Eunotia*, Frag = *Fragilaria*, Frus = *Frustulia*, Gomeis = *Gomphoneis*, Gopma = *Gomphonema*, Gyro = *Gyrosigma*, Hantz = *Hantzschia*, Luti = *Luticola*, Melo = *Melosira*, Navi = *Navicula*, Nitz = *Nitzschia*, Pinn = *Pinnularia*, Plano = *Planothidium*, Rhop = *Rhopalodia*, Sella = *Sellaphora*, Stau = *Stauroneis*, Suri = *Surirella*, Pleura = *Pleurosira*, Tryb = *Tryblionella*. Hard = Hardness, TDS = Total dissolved solids, Cond = Conductivity, Turb = Turbidity, BOD$^5$ = Biological Oxygen Demand after 5 days, Temp = Temperature, TSS = Total suspended solids, Ammon = Ammonium.

are generally described to be capable of tolerating critically polluted waters (Joh, 2012; Taylor et al., 2007).

There are some genera that are located near the intersection of axis 1 and 2. Examples of these genera are *Nitzschia* (Nitz) and *Navicula* (Navi) which indicates that these genera do not show any major sensitivity or reactivity towards different Physicochemical conditions and thus able to occupy a wide niche (Taylor et al., 2007; Taylor & Cocquyt, 2016). In other words, *Nitzschia* and *Navicula* are able to occupy wide ranges of ecological conditions and environmental gradients. Lastly, other genera near the origin point also exhibit the similar properties, albeit different reactivity or sensitivity based on their position between the two axes.

Genera that respond to local standards of water quality are considered to be environmentally important. The physicochemical conditions of rivers or streams are reflected in the assemblage and abundance. Based on the biplot presented in figure 3, *Cymbella* and *Stauroneis* respond to nitrate, *Fragilaria* and *Gomphoneis* to iron, *Pleurosira* to TSS, *Surirella* to Phosphate, *Sellaphora* and *Hanztchia* to pH and BOD, *Rihopalodia* and *Tryblionella* to temperature, *Nitzschia* to DO, and *Navicula* to TSS and Phosphate. The responsiveness of the genera towards the Physicochemical variables do not solely dictate presence and abundance but nevertheless offer a degree of understanding towards why the assemblage and abundance presents as such.

Pollution values for each genus were calculated (Table 4) and values range from 0.53 to 7.43. High PVT values indicate that the genera is able to tolerate disturbance and can occupy a wider ecological range, while lower values indicate more sensitivity or only occupies a narrow

**Table 4.** Pollution tolerance values for genera found in the study. Higher values indicate more tolerance for disturbance.

| Genera | PVT values | Genera | PVT values |
|---|---|---|---|
| *Achnanthidium* | 7.43 | *Stauroneis* | 7.16 |
| *Cocconeis* | 7.43 | *Cymbella* | 6.90 |
| *Fragilaria* | 7.43 | *Gyrosigma* | 6.90 |
| *Gomphoneis* | 7.43 | *Tryblionella* | 6.63 |
| *Gomphonema* | 7.43 | *Melosira* | 6.37 |
| *Luticola* | 7.43 | *Cyclotella* | 5.31 |
| *Navicula* | 7.43 | *Rhopalodia* | 4.78 |
| *Nitzschia* | 7.43 | *Frustulia* | 3.72 |
| *Pinnularia* | 7.43 | *Eunotia* | 2.92 |
| *Surirella* | 7.43 | *Diploneis* | 2.12 |
| *Achnanthes* | 7.16 | *Epithemia* | 2.12 |
| *Amphora* | 7.16 | *Hantzschia* | 1.86 |
| *Encyonema* | 7.16 | *Sellaphora* | 0.53 |
| *Planothidium* | 7.16 | *Pleurosira* | 0.53 |

ecological niche. Genera with high PVT values are consistent with known autoecologies; such of *Achnanthes*, *Achnanthidium*, *Navicula*, Nitzchia, and *Pinnularia* which are known to have species occupying wide niches; low to high conductivity, oligotrophic to hypereutrophic levels of biological activity, and acidic to alkaline pH levels (Holmes et al., 2022; Joh, 2012; Lange-Bertalot et al., 2017; Lee, 2012; Ponader & Potapova, 2007; Spaulding et al., 2021). On the other hand, diatoms with low PVT values such as *Pleurosira*, *Sellaphora*, and *Hantzschia* are sensitive and occupy narrow niches which can be characterized by a combination of different physicochemical conditions. An example is the genus *Pleurosira* which is typically found in highly polluted waters (Joh, 2010; Taylor & Cocquyt, 2016). *Sellaphora* are widespread in alkaline to brackish waters of neutral pH (Spaulding et al., 2021) but can tolerate strongly polluted conditions (Taylor et al., 2007) such as in eutrophic to hypereutrophic waters with moderate to high conductivity (Taylor & Cocquyt, 2016). *Hantzschia* are characteristic of intermittent aquatic habitats and often the genus is indicative of being washed from terrestrial habitats (Spaulding et al., 2021). As physicochemical conditions are often changing due to the dynamism of river systems, sustained conditions of transient or multiple combinations of conditions are often transient and may not be sustained for longer periods of time which may affect occurrence and abundance of sensitive diatoms.

The A5-PDI-TRB (%) is the index developed to reflect the degree of disturbance in the river basin. The A5-PDI-TRB (%) showed a range of scores from 0.00 to 21.37% (Table 5). Based on the A5-PDI-TRB (%) data, the following classification scale was developed to differentiate the areas according to the degree of disturbance.

Ten (10) areas were under the high disturbance classification, namely Mat-i, Sta. Ines, Omagling, Dalirig, San Miguel, Dalwangan, Kibalabag, Muhon, Natumolan and San Martin (Figure 4). All of the areas that are classified as highly disturbed are surrounded by anthropogenic influences such as human settlements and/or agriculture related land use, thus explaining the high index values. Furthermore, measurements of Physicochemical variables from these areas have at least one (1) variable above the recommended values for Class A waters and diatom assemblage are represented by more tolerant genera. In terms of elevation, three (3) areas in the upstream are classified as disturbed, two (2) in the midstream, and five (5) in the downstream area.

The most common and abundant genera among the highly disturbed areas are *Achnanthidium*, *Cocconeis*, *Gomphonema*, and *Navicula*. PVT values for the aforementioned genera are 7.43,

**Table 5.** A5-PDI-TRB (%) scores of representative aquatic systems in the sampling areas of the Tagoloan River Basin. (<7.25% = Low disturbance, 7.25% – 14.25% = Moderate disturbance, >14.25% = High disturbance)

| Sampling Area | A5-PDI-TRB (%) | Sampling Area | A5-PDI-TRB (%) |
|---|---|---|---|
| Omagling | 21.37 | Sumalsag | 12.54 |
| San Miguel | 21.12 | Poblacion (Malitbog) | 11.41 |
| Natumolan | 21.04 | Poblacion (Impasug-ong) | 11.33 |
| Kibalabag | 18.39 | La Fortuna | 10.97 |
| Muhon | 18.02 | Impalutao | 10.53 |
| Sta. Ines | 16.06 | Tangkulan | 10.04 |
| Mat-i | 15.04 | Siloo | 9.69 |
| Dalirig | 14.91 | Cawayan | 9.12 |
| San Martin | 14.81 | Diklum | 8.30 |
| Dalwangan | 14.67 | Puntian | 8.16 |
| San Vicente | 14.05 | Lunokan | 7.99 |
| Sta. Cruz | 13.84 | Patpat | 7.49 |
| Sto. Nino | 13.72 | Maluko | 5.40 |
| Sangkanan | 13.25 | Capitan Bayong | 0.00 |

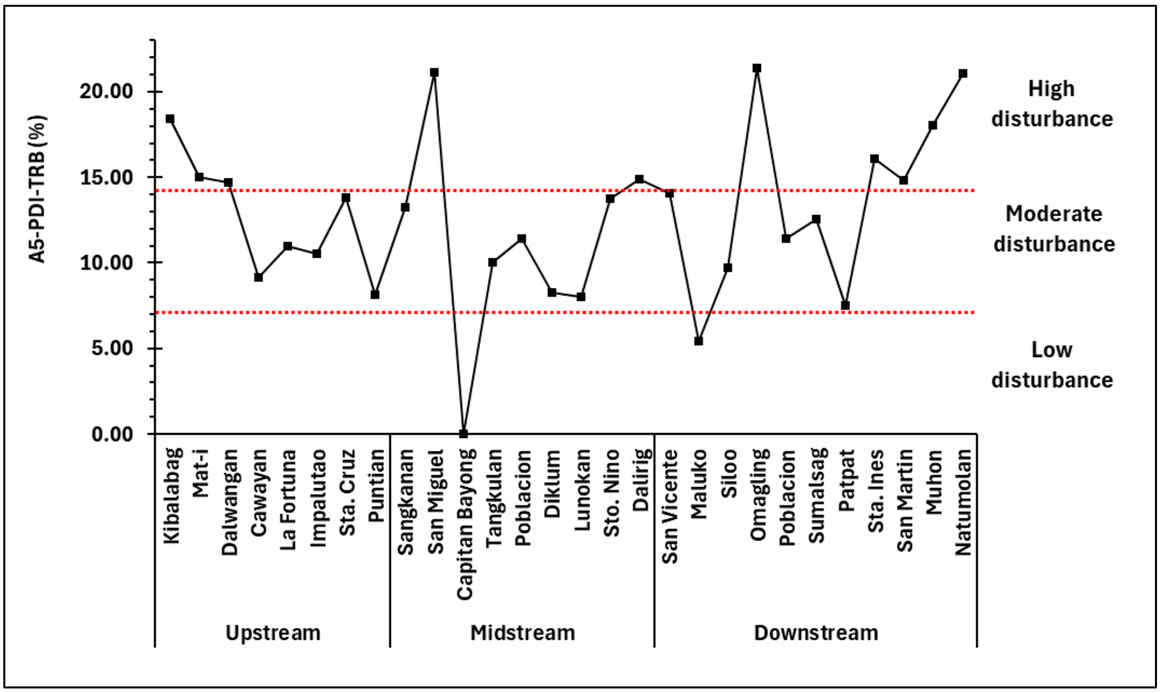

**Fig. 4.** A5-PDI-TRB (%) values for aquatic systems in sampling areas of Tagoloan River Basin arranged from highest to lowest elevation. Target lines delineate the disturbance classification. (<7.25% = Low disturbance, 7.25% – 14.25% = Moderate disturbance, >14.25% = High disturbance).

exhibiting the most tolerant genera. CCA ordination also support implications of the tolerance values for the most tolerant taxa such as *Navicula* are positioned near the intersection of Axis 1 and 2, indicating stable representation in occurrence and abundance throughout different and variable environmental conditions. *Navicula* is known to be widespread and can be dominant in oligotrophic and eutrophic conditions, as well as acidic to alkaline habitats (Kulikovskiy et al., 2021). *Achnanthidium* is known to be found in waters with varying trophic states, and most species are thought to occur in well oxygenated waters (Taylor & Cocquyt, 2016). Species of *Cocconeis* can occupy acidic to alkaline waters at various trophic levels, similar to *Navicula* and thus exhibit wide ecological niches. Cocconeis species such as *Cocconeis placentula* are also known to exhibit adaptability to fresh to brackish waters, pH, habitat patterns, and capable to cause red tides (Fu et al., 2022). Species of *Gomphonema* are widely distributed all over the globe (Jüttner et al., 2004) and can be found in both low and moderate conductivity areas. Greater adaptability indicates a possibly wider occupied niche. The presence of human influence and diatom PVT values explain the highly disturbed classification of the *A5-PDI-TRB* index to several aquatic systems in areas of the river basin.

Literature supports that rural areas with higher elevation and farther from the coastal cities are less subject to urbanization and anthropogenic inputs especially in Asian countries (Flückiger & Ludwig, 2018; Jayanthakumaran et al., 2019). However, the river at Kibalabag did not conform to this pattern based on the developed index as it was classified to be highly disturbed. This can be explained by the recent developments in the area. It is now a notable tourist spot in its province with multiple businesses such as vacation houses and some ongoing constructions to accommodate tourists. The high TSS levels may be indicative of the increased human activities since high TSS measurements are associated with construction and other building related human activities (Ghosh et al., 2023), thus the index detected the signs of human disturbance. This phenomenon of 'extended urbanization' is likely as rural populations are being overtaken by the expansion of urban areas and economic growth (Jayanthakumaran et al., 2019).

Sixteen (16) areas were classified as moderately disturbed based on the A5-PDI-TRB index. The most abundant genera in moderately disturbed areas are *Achnanthidium*, *Cocconeis*, and *Navicula*. These diatoms are the same with the most abundant genera in the high disturbance areas. Although both moderate and highly disturbed areas share the same most abundant genera, the two are differentiated in terms of assemblage. Moderately disturbed areas have lesser number of genera that have high PVT values while highly disturbed areas were characterized by more high PVT genera. Areas such with moderately disturbed classifications may be good target areas for mitigation and intervention since disturbance levels may still be curbed back to lower levels. Only two (2) areas were classified to be of low disturbance. The river in Capitan Bayong has less human influence due to their relatively remote distance from human settlements, industrial, and agricultural areas. Visible human influence in the area is a small bridge for vehicles to pass through the stream, and some dikes to support the bridge area. The river in Maluko on the other hand is located deeper into the dense vegetation areas, limiting human interaction with the aquatic system. The lesser anthropogenic influence on the two areas explains the low disturbance classification. It is important that these areas be priorities for conservation and mitigation of human influence since these areas may serve as reference sites for relatively low disturbance aquatic systems.

## CONCLUSION

Canonical correspondence analysis revealed the relationship of diatoms to the Physicochemical variables, with some taxa being responsive to variables with locally set standards, allowing for diatoms to be a useful tool for local aquatic system monitoring and assessments. Calculated PVT values for each genera profiled diatoms in terms of tolerance to disturbance, considering local standards and guidelines for water quality. PVT values for tolerant taxa were consistent to known genera autoecologies. A local diatom-based index was successfully developed and performed well to reflect the degree of disturbance of the aquatic systems sampled. Ten (10 areas) were classified as highly disturbed, 16 as moderately disturbed, and 2 areas with low disturbance. Moderate and low disturbance areas are recommended to be prioritized in conservation efforts as these areas may still be reversible in terms of disturbance levels, and low disturbance areas may also serve as a reference for good water quality and ecological status of aquatic systems in river basin. In addition, the index utilized genera level identification of diatoms, which eases specialization burdens of having diatom species-level taxonomists for monitoring purposes. This encourages the usage of diatoms as a tool for routine water quality and ecological assessments in developing countries, offering a cheaper alternative to traditional Physicochemical testing. Furthermore, this index shows a longer snapshot of the disturbance as it capitalizes on biological components which are not as fleeting as in-situ or ex-situ Physicochemical analysis. The developed index will serve as starting point to a larger goal of developing a wider ranged index, encompassing multiple river systems and regions.

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## CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

## LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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