**ICYANO: a cyanobacterial bloom vulnerability index for drinking water treatment plants**


**ABSTRACT**

Managing freshwater systems has become a challenge for global water utilities given that cyanobacterial blooms have been increasing in frequency and intensity. Consequently, a water quality index that uses conventional measurements to assess toxic cyanobacterial hazards and guide the selection of proper treatment technologies could benefit water resource managers about water quality parameters routinely analyzed in line with environmental changes. An index model, called Icyano, showed that chlorophyll-α, cyanobacterial concentration, and total nitrogen were most important for the index. All reservoirs classified as good by Icyano used direct filtration water treatment technology. Many of the medium Icyano-classified reservoirs used a pre-treatment unit followed by a direct filtration unit. Two reservoirs that were classified as bad or very bad have been utilizing pre-treatment + direct filtration or a complete cycle technology, respectively. As the Icyano index increases, water treatment plants should switch from direct filtration to using a pre-treatment to improve finished water quality. Findings from this project suggest that the direct filtration technology initially used in water treatment plants is not capable of meeting the current water quality guidelines in reservoirs that contain adverse water quality conditions, mostly related to an increase in toxic cyanobacterial blooms. As such, based on our findings, we recommend prioritizing financial resources towards pre-treatment technology or changes to more advanced technologies when Icyano index values increase.

**Key words** | harmful algae, water quality, water quality tool, water treatment plants, water treatment technologies

**HIGHLIGHTS**

- A new index for assessing cyanobacterial hazards (icyano) in drinking water reservoirs was developed.
- Chlorophyll, total nitrogen, and cyanobacterial concentration were the three most important parameters to the Icyano index.
- A high N:P may best explain the dominance of cyanobacteria in the reservoirs.
- As Icyano increases, water treatment plants should switch to more complex treatments.

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INTRODUCTION

Anthropogenic eutrophication and changing climate, such as increasing drought or flooding, have increased toxic cyanobacterial bloom (cyanoHABs) frequency and intensity worldwide (Paerl & Paul 2012; Bakker & Hilt 2016; Zhao et al. 2015). The increase in cyanoHAB events has greatly affected surface drinking water supplies in many parts of the world, including northeastern Brazil (CAGECE 2019), and led to difficulties in managing water resources. Certain species of cyanobacteria may produce a wide variety of toxic secondary metabolites (e.g. microcystins, saxitoxins, nodularins, cylindrospermopsins) (Carmichael 1994; Mohamed et al. 2006; Van Apeldoorn et al. 2007), which are linked to a variety of deleterious effects on the liver, kidney, heart, gonads, and nervous system of both fish and mammals (Zhao et al. 2019). Furthermore, cyanobacteria may produce taste and odor compounds, such as 2-methylisoborneol (MIB) and geosmin, which are non-toxic but make the water unpalatable to consumers and give the perception of overall poor water quality (Parinet et al. 2010; Pestana et al. 2014; Edwards et al. 2017).

According to the United Nations (2011), drylands (otherwise known as arid and semi-arid regions) occupy about 41.3% of the world’s land surface and are populated by approximately two billion people. Moreover, the majority of people who lack access to clean drinking water reside in semi-arid regions from sub-Saharan Africa, Asia, and Latin America (Walter et al. 2018; WHO 2019). The semi-arid region classification is mainly based on rainfall irregularity, in which annual rainfall ranges from 300 to 500 mm. Ceará State, in northeastern Brazil, is characterized by an annual rainfall average below 600 mm (FUNCEME 2017), the majority of which is distributed between February and May. However, precipitation is often irregular, leading to prolonged droughts and frequently resulting in the drying-out of waterbodies (Walter et al. 2018). Additionally, this region has a precipitation/evapotranspiration ratio between 0.2 and 0.5 (FUNCEME 2017), and high temperatures (23–27°C) and ambient sunlight (2,800 hr·year⁻¹). Due to its equatorial climate, harmful algal blooms are more likely to occur in freshwater reservoirs from semi-arid regions in Brazil. CyanoHABs are favored by surface water accumulation in shallow reservoirs with high hydraulic retention time, high average temperature, high solar radiation, and overall intensive anthropogenic activities that lead to elevated nutrient inputs. Furthermore, prolonged thermal stratification conditions that coincide with a rainy season that promotes excessive enrichment of nutrients have also been reported as a main cause of CyanoHABs in northeastern Brazil (Dantas et al. 2011; Barros et al. 2019; Zhang et al. 2020). There is a serious threat to potable drinking water supplies in semi-arid regions, like Ceará State, that exhibit elevated temperatures, high sunlight, and persistent drought conditions due to a changing climate (Marengo 2009) that are linked to current and forecasted cyanobacterial bloom events (Brasil et al. 2016; Moura et al. 2017).

Reports of cyanobacterial intoxication (Falconer 1995; Carmichael 2001; Backer et al. 2010) have led to several policy decisions focused on protecting freshwater systems worldwide, especially those related to drinking water.
supplies (Leigh et al. 2010). However, toxic cyanobacteria in water are the result of associations among anthropogenic nutrient pollution and other factors, such as geographical features and disturbances stemming from climate change (Barros et al. 2019; Fadel et al. 2019; Mukundan et al. 2020). Assessing water quality parameters individually can be a complicated practice involving numerous chemical, physical, and biological measurements that are often interacting and/or unexplored (UNEP 2007; Bharti & Katyal 2011; Srebotnjak et al. 2011; Srivastava & Kumar 2013; Garcia et al. 2018), especially considering the relatively ease to access large environmental datasets. As an alternative, water quality indices that utilize an algorithm to synthesize different types of data into a single number are becoming more common and useful for classifying water quality trends over time and in different geographic areas (Poonam et al. 2013).

Early water quality indices, such as that proposed by Horton (1965), have been refined to improve their accuracy and modified for targeted locations (Ewaid & Abed 2017), especially in areas that are subject to deterioration due to natural or anthropogenic impacts (Poonam et al. 2013). In general, these approaches consist of summarizing a set of interconnected parameters by a single numerical value situated on a fixed scale that allows users to quickly evaluate and rank water quality for efficient management decisions. Due to its reductionist character, in which several quality items are converted into a score or single evaluation, indices are controversial, since they can may overlook important conditions that occur in a waterbody (Nasiri et al. 2007). Despite its intrinsic limitations, the synthesizing capacity provided by an index, is of great importance to the public and managers who need simple tools for making important management decisions and to prioritize financial resources (Srebotnjak et al. 2011; Srivastava & Kumar 2013; Garcia et al. 2018). However, limited published studies on indices that evaluate water quality regarding the potential hazards of cyanobacteria and their metabolites exist. This knowledge gap makes decision-making in the water quality industry more challenging, especially when it comes to selecting the proper technology for water treatment.

Conventional water treatment, composed of chemical coagulation/flocculation, sedimentation, and granular media filtration processes, is the most used technology for municipal water treatment. However, some developing countries, including Brazil, regularly utilize direct and double filtration due to its low cost of construction and operation. Direct filtration is composed of chemical coagulation followed by a single pass through a granular media filter while in double filtration water goes through two granular media filters after chemical coagulation. Direct filtration has been demonstrated to be able to meet drinking water guidelines for source waters with low cyanobacterial concentrations, low turbidity, and apparent color. However, when water quality decreases, one should consider using double filtration or, in the worst-case scenario, conventional treatment. The challenge for water companies is to identify what technology to adopt given their current water quality parameters while considering water quality guidelines and economic aspects. Over the last 40 years in semi-arid region of Brazil, current water treatment plant (WTP) technologies have become outdated, and it has often been necessary to add a pre-treatment step to manage the increase in cyanobacteria and their associated toxins (CAGECE 2019; COGERH 2019). Institutional managers must rely on technical and synthesized data to support the allocation of funds and resources regarding the status and management of water quality (Srebotnjak et al. 2011). Therefore, the goals of this work were to develop a new water quality index, called Icyano, for assessing cyanobacterial and their associated toxins in artificial reservoirs used for drinking water production as well as to identify which water treatment plant processes are most vulnerable to cyanobacterial hazards to inform water treatment companies where to prioritize resources.

**MATERIALS AND METHODS**

**Study region**

This study used data collected from 2013 to 2017 in 20 drinking water reservoirs within the Ceará State, northeastern Brazil (2° 30’ 00″ - 8° 52’ 00″ South and 37° 14’ 00″ - 41° 30’ 00″ West; Figure 1 and Table 1). The climate of this area is considered tropical hot and semi-arid (type ‘BSh’, Köppen climate classification; NETO et al. 2014; IPECE 2017). The water reservoirs studied in the Ceará State are mainly used...
for human and animal consumption, but also fish farming, agriculture, industrial demands, and flow regulation (COGERH 2019).

**Field sampling and analytical methods**

From 2013 to 2017, samples were collected in duplicate (monthly or weekly) at water intakes 30 cm below the surface at water treatment plants (WTP) used by the Water and Wastewater Company of Ceará (CAGECE). Sampling frequency was based on the prevalence of cyanobacteria, as Brazilian legislation calls for standard monthly sampling increased to weekly sampling when cyanobacterial concentrations in reservoirs exceed 20,000 cells mL\(^{-1}\). Although many water quality parameters have been used in the water industry, temperature, evaporation, sunlight, electrical conductivity, chlorophyll, total nitrogen, total phosphorus, Secchi depth, and concentration of cyanobacteria were adopted for the proposed model since they have been commonly monitored by the local water companies and are readily available. As a criterion for sample selection in this model, we included samples that contained concentrations of microcystin and saxitoxin >1 \(\mu\)g L\(^{-1}\), which resulted in 2,489 samples used in the model (total samples analyzed 24,169).

For phytoplankton analyses, samples were preserved with 1% Lugol’s solution, while biological material used *in vivo* was kept refrigerated to decrease organism metabolism and oxygen consumption in the absence of light. Phytoplankton cell counts were carried out with a Sedgewick-Rafter counting chamber. On average, fields were counted at multiple magnifications (200x and 400x, depending on the size of the phytoplankton taxon) until at least 100 individuals of the most frequent species or 400 individuals in total were counted (Lawton 1999; APHA 2012; Barros et al. 2019).
Although testing for cylindrospermopsin is only recommended by Brazilian guidelines, the lakes monitored were also tested for this toxin and no significant concentrations were found, as reported by Barros et al. (2019). Therefore, cylindrospermopsin was not considered a factor of concern in our region. Two cyanobacterial toxins, microcystin and saxitoxin, were measured using enzyme-linked immunosorbent assays (ELISA) according to the manufacturer directions (Abraxis LLC 2007; Abraxis LLC 2009). These ELISA kits recognize saxitoxin or a specific antibody moiety (-ADDA) found in many microcystin variants. The minimum reporting level (MRL) for the assays were 0.02 and 0.15 μgL⁻¹ for saxitoxin and microcystin-LR equivalents, respectively (Abraxis, LLC, Warminster, Pennsylvania). Nutrient concentrations were analyzed following the persulfate method for the simultaneous determination of total nitrogen and total phosphorus (APHA 2022). Meteorological data, including temperature, precipitation, evaporation, and irradiation, were collected at weather stations monitored by the Foundation of Meteorology and Water Resources of Ceará (FUNCEME) and National Institute of Meteorology of Brazil (INMET).

**Modeling the cyanobacterial index (Icyano)**

The cyanobacterial index, *Icyano*, was calculated for each reservoir using a three-pronged approach. First, Pearson’s correlation coefficients were used as an estimate of the strength and direction of the relationship between each environmental parameter. Secondly, the Kaiser-Meyer-Olkin (KMO) adequacy test was performed to check whether the correlation structure of the dataset was suitable for factorial analysis (third and final approach) and index development (i.e. KMO >0.6; Hair et al. 1987; Parinet et al. 2010; Te & Gin 2011). The KMO value for this study was 0.62, so a factorial analysis was used to identify important latent variables (i.e. common factors loads).

**Table 1 | Characteristics of the studied reservoirs including trophic classification according to COGERH (2019)**

<table>
<thead>
<tr>
<th>Code</th>
<th>Reservoir</th>
<th>Trophic classification a</th>
<th>Capacity (m³)</th>
<th>Hydraulic basin (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>Acarape do Meio</td>
<td>Mesotrophic</td>
<td>31,500,000</td>
<td>220</td>
</tr>
<tr>
<td>AMR</td>
<td>Amanari</td>
<td>Eutrophic</td>
<td>11,010,000</td>
<td>271</td>
</tr>
<tr>
<td>AR</td>
<td>Aracoiba</td>
<td>Eutrophic</td>
<td>170,700,000</td>
<td>1,506</td>
</tr>
<tr>
<td>AT</td>
<td>Trussu</td>
<td>Eutrophic</td>
<td>301,000,000</td>
<td>5,509</td>
</tr>
<tr>
<td>BO</td>
<td>Boqueirão</td>
<td>Hypereutrophic</td>
<td>28,110,000</td>
<td>512</td>
</tr>
<tr>
<td>CN</td>
<td>Canafístula</td>
<td>Eutrophic</td>
<td>13,110,000</td>
<td>315</td>
</tr>
<tr>
<td>E</td>
<td>Ema</td>
<td>Hypereutrophic</td>
<td>10,390,000</td>
<td>284</td>
</tr>
<tr>
<td>EQ</td>
<td>Edson Queiroz</td>
<td>Hypereutrophic</td>
<td>254,000,000</td>
<td>2,660</td>
</tr>
<tr>
<td>FQ</td>
<td>Forquilha</td>
<td>Hypereutrophic</td>
<td>50,132,000</td>
<td>923</td>
</tr>
<tr>
<td>G</td>
<td>Gavião</td>
<td>Eutrophic</td>
<td>32,900,000</td>
<td>618</td>
</tr>
<tr>
<td>MRT</td>
<td>Martinopole</td>
<td>Hypereutrophic</td>
<td>23,200,000</td>
<td>647</td>
</tr>
<tr>
<td>MT</td>
<td>Monsenhor Tabosa</td>
<td>Hypereutrophic</td>
<td>12,100,000</td>
<td>185</td>
</tr>
<tr>
<td>MU</td>
<td>Mundaú</td>
<td>Eutrophic</td>
<td>21,300,000</td>
<td>123</td>
</tr>
<tr>
<td>PM</td>
<td>Pereira de Miranda</td>
<td>Hypereutrophic</td>
<td>395,638,000</td>
<td>5,700</td>
</tr>
<tr>
<td>PS</td>
<td>Paulo Sarasate</td>
<td>Hypereutrophic</td>
<td>891,000,000</td>
<td>9,600</td>
</tr>
<tr>
<td>PT</td>
<td>Patú</td>
<td>Hypereutrophic</td>
<td>71,829,000</td>
<td>856</td>
</tr>
<tr>
<td>PU</td>
<td>Puiu (Parambú)</td>
<td>Eutrophic</td>
<td>8,530,000</td>
<td>159</td>
</tr>
<tr>
<td>SD</td>
<td>Serafim Dias</td>
<td>Hypereutrophic</td>
<td>43,000,000</td>
<td>688</td>
</tr>
<tr>
<td>SN</td>
<td>Sítios Novos</td>
<td>Hypereutrophic</td>
<td>126,000,000</td>
<td>2,010</td>
</tr>
<tr>
<td>T</td>
<td>Trapia III</td>
<td>Eutrophic</td>
<td>5,510,000</td>
<td>130</td>
</tr>
</tbody>
</table>

aTrophic classification based on Carlson (1977) adapted for tropical reservoirs by Toledo et al. (1983).
A factorial analysis is a widely used technique for the construction of indexes (Meireles et al. 2010). This multivariate statistical technique aims to summarize and reduce data dimensions while analyzing the relationships between variables and defining a set of common latent variables. Through this technique, it is also possible to calculate the weight represented by each variable for the index composition \(W_i\) (Hair et al. 1998; Johnson & Wichern 2007). The cyanobacterial index (Icyano) was calculated according to the following equation:

\[
Icyano = \sum_{i=1}^{n} QiWi
\]

where, Icyano is a dimensionless parameter ranging from 0 to 100; \(Q_i\) represents a standardized variable (0–100), it is the quality of the \(i\)th parameter and a function of its concentration or measurement; \(W_i\) is the normalized weight of the \(i\)th parameter and a function of its importance in explaining the global variability in water quality. \(W_i\) is described according to the following equation:

\[
W_i = \frac{F_j A_{ij}}{\sum_{j=1}^{k} \sum_{l=1}^{n} F_j A_{lj}}
\]

where, \(F_j\) is component 1 eigenvalue; \(A_{ij}\) is the explanatory power of parameter \(i\) by factor \(j\); \(i\) is the number of parameters selected by the model, ranging from 1 to \(n\); \(j\) is the number of factors selected in the model, varying from 1 to \(K\).

Statistical tests and modeling were performed using the software R with the complot and psych packages. An analysis of variance (ANOVA) followed by a Tukey test were also used to further test relationships observed with the Icyano index. Based on the calculated Icyano index score, each reservoir was then classified into one of four water quality classification categories according to Shweta et al. (2015) and Ewaid & Abed (2017). The classification categories were Icyano range from 0 to 25: Good (G); 26–50: Medium (M); 51–75: Bad (B); 76–100: Very Bad (VB). Each reservoir Icyano index was then compared with the technology used at the WTP adjacent to that reservoir.

**RESULTS**

**Environmental variables**

Relatively little variability (i.e. \(\mu > \sigma\)) was observed in the climatological variables across the 20 study reservoirs (Appendix A in the supplementary material provides the descriptive statistics of the analyzed parameters). Such findings are not surprising considering the inland area of northeastern Brazil consistently exhibits high temperatures and low thermal amplitudes (INMET 2016; FUNCEME 2017; IPECE 2017). In contrast, water quality varied widely across the 20 reservoirs, including in cyanobacterial diversity (Figure 2). Additionally, two analyzed cyanobacterial toxins, microcystins (MC) and saxitoxins (STX), differed greatly across the reservoirs (Figures 3 and 4). Despite 13 reservoirs having detectable microcystins >0.15 \(\mu\)g L\(^{-1}\), seven (AM, E, FQ, MRT, PU, SD and SN reservoirs) had MC concentrations >1 \(\mu\)g L\(^{-1}\) \((p > 0.05;\) Figure 3(a)), a limit that exceeds World Health Organization guidelines for microcystin-LR (WHO 2017). The colony-forming order Chroococcales dominated in the MRT reservoir (Turkey’s \(P < 0.05;\) Figure 2), while FQ and PU reservoirs contained high abundances of Raphidiopsis raciborskii. Interestingly, this cyanobacteria is not known to produce microcystins. Furthermore, these two reservoirs also contained detectable concentrations of saxitoxin. There seems to have been a competition or succession in the cyanobacterial community, and it may have influenced toxin production favoring microcystins. Although nine reservoirs had detectable saxitoxins greater than 0.11 \(\mu\)g L\(^{-1}\) (AM, BO, CN, EQ, FQ, MT, PS, PU and T; \(p > 0.05;\) Figure 3(b)), only one reservoir (BO) surpassed WHO guidelines for this toxin (\(>3 \mu\)g L\(^{-1}\); WHO, 2019; \(P > 0.05;\) Figure 3(b)). R. raciborskii represented approximately 80% of cyanobacteria in that reservoir and was the dominant species in seven additional reservoirs (AM, CN, EQ, FQ, MT, PU and T; Turkey’s \(P < 0.05\)). Planktothrix agardhii and R. raciborskii dominated in the PS reservoir; this time, saxitoxin production was clearly prevalent (Figure 3(b)).

As expected, chlorophyll concentration showed a moderate inverse correlation with Secchi depth (\(r = -0.574; p = 0.008\)) and was positively correlated with cyanobacterial
concentration ($r = 0.588; p = 0.006$). A positive correlation was observed between total nitrogen (TN) and chlorophyll-a (Chl) ($r = 0.811; p = 0.000014$) as well as cyanobacterial density (Cyano) ($r = 0.549; p = 0.012$), but was inversely correlated with Secchi depth ($r = -0.586; p = 0.006$). Lastly, a strong positive correlation was observed between temperature (temp) and evaporation (Evap) ($r = 0.753; p = 0.00013$). The complete Pearson correlation matrix is provided in Table 2. A Bartlett’s test ($p = 2.2 \times 10^{-16}$) suggested that variances differed among the reservoirs studied (see factorial results in Table 3).

### Icyano classifications

Reservoirs AM, AT, G, and MU were classified as good (G), while FQ and MT were classified as very bad (VB) by Icyano (Table 4). The calculated Icyano index generally followed the trophic classification assigned to the reservoir with a few exceptions; three reservoirs given a eutrophic classification were deemed ‘good’ by Icyano. On the other hand, water treatment technology robustness (direct filtration < double filtration < conventional treatment) did not follow the worsening of water quality, apparently because the company responsible for the treatment does not have a proper procedure to guide the selection of the necessary treatment technology during the WTP design and construction phases. This means that although some facilities were capable of using higher-quality treatment methods, they chose not to due to a lack of awareness of apparent water quality. For example, as Icyano increases (i.e. water quality deteriorates), the treatment technology involved did not change from a simple treatment technology (direct filtration) to a more robust one (conventional treatment) to meet drinking water guidelines (Table 4), as would be expected.

Although the reservoirs classified as good were dominated by cyanobacteria, reservoirs AM, G, and MU had higher cyanobacterial diversities (Figure 2). Aphanocapsa sp. represented more than 85% of the cyanobacterial composition of reservoir AT ($r = 0.811; p = 0.000014$) as well as cyanobacterial density (Cyano) ($r = 0.549; p = 0.012$), but was inversely correlated with Secchi depth ($r = -0.586; p = 0.006$). Lastly, a strong positive correlation was observed between temperature (temp) and evaporation (Evap) ($r = 0.753; p = 0.00013$). The complete Pearson correlation matrix is provided in Table 2. A Bartlett’s test ($p = 2.2 \times 10^{-16}$) suggested that variances differed among the reservoirs studied (see factorial results in Table 3).

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technology initially designed (direct filtration) for double filtration. The PU, FQ and SD reservoirs, being newer WTPs, have already been designed with greater robustness with more treatment steps (conventional treatment).

In this study, we found that the best model to predict dissolved microcystin concentration incorporated chlorophyll-α, TP, TN, DOC, and the interaction between temperature and chlorophyll-α among others. These findings reinforce the model developed by Walls et al. (2018) on overall water quality; however, we were able to increase the power of our index with the inclusion of variables, like evaporation, sunlight, conductivity, Secchi depth, and cyanobacterial concentration. Additionally, we were able to rank the strength of the relationships between the observed variables from strongest to weakest using Pearsons correlation coefficients: TN & Chl ($r = 0.811$), Temp & Evap ($r = 0.753$), Chl & Cyano ($r = 0.588$), TN & Secchi ($r = -0.586$), Chl & Secchi ($r = -0.574$), TP & CE ($r = -0.526$), and TP & Sunlight ($r = -0.526$) (Table 2). Furthermore, it should be noted that total nitrogen, chlorophyll-α, and cyanobacterial concentration accounted for 60% of the model composition.
DISCUSSION

According to Huang et al. (2016), global warming trends are particularly intensified in semi-arid regions, with droughts becoming longer and more severe with higher evaporation and lower precipitation. The most noticeable consequences of high temperatures and the other climatic forecasts in reservoirs, like those studied in the Ceará region, is the

Figure 4 | Location of each reservoir studied, classification of the mean concentration of microcystin (MC), saxitoxin (STX), and icyano classification. *Results of cyanotoxins are provided in μgL⁻¹.

| Location of each reservoir studied, classification of the mean concentration of microcystin (MC), saxitoxin (STX), and icyano classification. *Results of cyanotoxins are provided in μgL⁻¹. | 1 | 2 | 3
---|---|---|---
Reservoirs | MC | STX | Icyano
MC | 0 - 1 | 0 - 3 | 0 - 25
STX | 1.01 - 1.5 | 3.01 - 3.5 | 25.01 - 50
Icyano | 1.51 - 2 | 3.51 - 4 | 50.01 - 75

Datum: SIRGA S 2000
0 25 50 100 200 km
significant decrease in water availability and quality. Studies conducted by The Inter-American Institute for Cooperation on Agriculture in 2002 affirmed that evaporation in semi-arid environments may reach 1,000 mm yr$^{-1}$ in coastal regions and more than 3,000 mm yr$^{-1}$ in inland areas. Bakker & Hilt (2016) also concluded that decreases in reservoir levels during the summer often lead to longer retention times as well as an increase in the accumulation of nutrients that may promote cyanobacterial blooms. Brasil et al. (2016) confirmed that this phenomenon may increase salinity (measured in this study as electrical conductivity). Low conductivity favors the presence of diazotrophic cyanobacteria, while high salinity typically favors the growth of taxa that do not produce heterocysts (Srivastava et al. 2009). All of which point to the importance and necessity for an index tool that can easily and accurately inform resource managers how to best alter their treatment methods to keep the distributed water at the highest quality possible.

The high, positive correlation between chlorophyll-$a$ and total nitrogen is not surprising and could be because cyanobacteria have a higher nitrogen requirement when compared to eukaryotic algae (Allen 1984). According to Dolman et al. (2012), nitrogen may have a stronger influence than phosphorus on eutrophication and concomitant shifts in phytoplankton community composition. According to these authors, the correlation between total cyanobacterial biovolume and TP became less significant at high TP concentrations but continued to increase linearly across a broader range of TN. Moreover, Lewis & Wurtsbaugh (2008) argued that nitrogen fixation is not always sufficient to overcome nitrogen limitation due to limitations in light or other microelements. Previous research also suggests a saturation between phosphorus concentration and cyanobacterial biovolume (Dolman et al. 2012) and biomass (Watson et al. 1997). All of which reinforce why total nitrogen and chlorophyll-$a$ comprise such a large part of the model.

Generally, TN:TP ratios were proportional to cyanobacterial concentrations. Not only were cyanobacteria heavily

<p>| Table 2 | Pearson correlation matrix for the variables studied for icyano |</p>
<table>
<thead>
<tr>
<th>Temp</th>
<th>Evap</th>
<th>Sunlight</th>
<th>TN</th>
<th>TP</th>
<th>Chl</th>
<th>CE</th>
<th>Sec</th>
<th>Cyano</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evap</td>
<td>0.753</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunlight</td>
<td>0.158</td>
<td>0.362</td>
<td>1</td>
<td></td>
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<tr>
<td>TN</td>
<td>0.169</td>
<td>0.369</td>
<td>0.115</td>
<td>1</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>TP</td>
<td>0.317</td>
<td>0.158</td>
<td>0.526</td>
<td>0.359</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chl</td>
<td>0.248</td>
<td>0.426</td>
<td>0.113</td>
<td>0.811</td>
<td>0.428</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CE</td>
<td>0.109</td>
<td>0.251</td>
<td>0.036</td>
<td>0.444</td>
<td>0.526</td>
<td>0.391</td>
<td>1</td>
<td></td>
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<tr>
<td>Sec</td>
<td>0.313</td>
<td>0.220</td>
<td>0.299</td>
<td>0.586</td>
<td>0.399</td>
<td>0.574</td>
<td>0.299</td>
<td>1</td>
</tr>
<tr>
<td>Cyano</td>
<td>0.456</td>
<td>0.334</td>
<td>0.063</td>
<td>0.549</td>
<td>0.163</td>
<td>0.588</td>
<td>0.022</td>
<td>0.394</td>
</tr>
</tbody>
</table>

Temp = temperature; Evap = evaporation; Sunlight = irradiation; TN = total nitrogen; TP = total phosphorus; Chl = chlorophyll; CE = electrical conductivity; Sec = Secchi depth; and Cyan = Cyanobacterial concentration. Units for each measurement are provided in Table 3.

*aVariables are independent ($p > 0.05$).

| Table 3 | Matrix for factorial loads estimating commonality and the weight of each variable ($W_i$) |
| Variables | Factor 1 | Factor 2 | Factor 3 | $W_i$ |
| Temp ($^\circ\text{C}$) | 0.289 | 0.755 | 0.106 | 0.073 |
| Evap (mm) | 0.243 | 0.936 | 0.243 | 0.061 |
| Sunlight (h) | 0.128 | 0.488 | 0.263 | 0.032 |
| TN (mg L$^{-1}$) | 0.759 | 0.392 | 0.439 | 0.202 |
| TP (mg L$^{-1}$) | 0.166 | 0.041 | 0.793 | 0.042 |
| Chl (mg L$^{-1}$) | 0.800 | 0.333 | 0.439 | 0.022 |
| CE ($\mu$S cm$^{-1}$) | 0.155 | 0.355 | 0.039 |
| Sec (m) | 0.577 | 0.209 | 0.341 | 0.145 |
| Cyano (cell mL$^{-1}$) | 0.851 | 0.209 | 0.277 | 0.214 |

Temp = temperature; Evap = evaporation; Sunlight = irradiation; TN = total nitrogen; TP = total phosphorus; Chl = chlorophyll; CE = electrical conductivity; Sec = Secchi depth; and Cyano = Cyanobacterial concentration.

*aInsignificant values.
abundant, but they were incredibly dominant in our study sites (Figure 2). This observation contradicts the findings of Smith (1985) who compiled data from 17 lakes worldwide and concluded that cyanobacteria tended to be rare when TN:TP exceeded 29. Furthermore, a similar study conducted by Havens et al. (2003) examined a 28-year long dataset from Lake Okeechobee, FL, USA. They found that as TN:TP decreased through the decades, cyanobacterial dominance increased. However, a recent study published by Li et al. (2018) examined a Swedish drinking water lake and found cyanobacteria dominated the phytoplankton community despite inflow TN:TP ratios being measured at upwards of 40. The findings of Li et al. (2018) could explain the patterns found in the reservoirs in this study. Slow-growing cyanobacteria are typically less palatable to grazers than eukaryotic green algae and this coupled with a constant source of high concentrations of N and P (among other nutrients) could encourage cyanobacterial dominance and the negative effects that are associated with them. Despite the importance of the TN:TP ratio, it was not added into the model because it exhibited high multicollinearity with TN and TP. In other words, there is very high intercorrelations or inter-associations among these independent variables (TP, TN, and TN:TP), which generates a disturbance within the model that can cause statistical inferences that make the model less reliable.

When warnings related to high cyanobacterial biomass and consequently potentially high cyanotoxin concentrations in the water supply are signaled, additional measures are required to ensure water quality and protect consumers (He et al. 2016). Additionally, when these warnings become increasingly frequent, water treatment technologies should be evaluated. With that being said, as this study was being carried out no such evaluation criteria existed. Therefore, many of the 20 WTPs associated with the studied reservoirs in this project used a less robust water treatment technology (direct filtration), and when their water quality was evaluated with the Icyano

### Table 4: Type of treatment used in the WTP of each reservoir; calculated value of the cyanobacterial index (Icyano) and classification of each reservoir

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Current water treatment technology</th>
<th>Trophic classification</th>
<th>Icyano index</th>
<th>Icyano classification</th>
<th>Action to be taken</th>
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<tbody>
<tr>
<td>AT</td>
<td>Direct filtration</td>
<td>Eutrophic</td>
<td>6.36</td>
<td>G</td>
<td>KT</td>
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<tr>
<td>G</td>
<td>Direct filtration</td>
<td>Eutrophic</td>
<td>22.13</td>
<td>G</td>
<td>KT</td>
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<tr>
<td>MU</td>
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<td>Eutrophic</td>
<td>23.39</td>
<td>G</td>
<td>KT</td>
</tr>
<tr>
<td>AM</td>
<td>Direct filtration</td>
<td>Mesotrophic</td>
<td>24.02</td>
<td>G</td>
<td>KT</td>
</tr>
<tr>
<td>AR</td>
<td>Direct filtration</td>
<td>Eutrophic</td>
<td>28.14</td>
<td>M</td>
<td>CT</td>
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<tr>
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<td>32.63</td>
<td>M</td>
<td>CT</td>
</tr>
<tr>
<td>AMR</td>
<td>Double filtration&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eutrophic</td>
<td>36.55</td>
<td>M</td>
<td>KT</td>
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<td>PU</td>
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<td>M</td>
<td>KT</td>
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<tr>
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<td>38.42</td>
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<td>CT</td>
</tr>
<tr>
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<td>44.19</td>
<td>M</td>
<td>KT</td>
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<tr>
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<td>44.29</td>
<td>M</td>
<td>CT</td>
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<td>45.94</td>
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<tr>
<td>SD</td>
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<td>48.32</td>
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<td>KT</td>
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<td>T</td>
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<td>Eutrophic</td>
<td>48.72</td>
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<td>77.64</td>
<td>VB</td>
<td>CT</td>
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</table>

<sup>a</sup>Adapted for double filtration, but initially designed for direct filtration (G – Good, M – Medium, B – Bad, and VB – Very Bad). KT – Keep WTP Technology; CT – Change WTP Technology.
index, scores closely represented the trophic state of the reservoir. This means that most of the WTPs in this study were likely undertreating their water when samples were collected. The proposed index could be an effective tool not only for selecting water treatment plant technology but also for the management of the multiple uses of water resources in the semi-arid regions. Although this index was developed and used data from semi-arid regions, harmful algal blooms are a global issue and the parameters that govern harmful blooms in semi-arid regions likely do so similarly around the world and may be used in other regions with success.

**CONCLUSIONS**

The parameters that best explained the proposed *Icyano* index were temperature, evaporation, sunlight, electrical conductivity, chlorophyll, TN, TP, Secchi depth, and concentration of cyanobacteria. However, chlorophyll-a, total nitrogen, and cyanobacterial concentration accounted for ~60% of the model composition, suggesting that water resource managers with limited infrastructure can still monitor their water quality effectively.

Across the study reservoirs, there was a low diversity of phytoplankton and an absolute dominance of cyanobacteria (greater than 90% of phytoplankton composition) highlighted by *R. raciborskii*. Apparently, competition between cyanobacteria species may be associated with the production of cyanotoxins, MC being the most common cyanotoxins found in studied reservoirs.

In this study, the direct filtration technology utilized in many WTPs was incapable of providing drinking water that met Brazilian potability and WHO standards due to the presence of cyanobacteria. WTPs initially designed to operate only with direct filtration now use pre-treatment technology (double filtration) or a conventional treatment to address this deficiency after being evaluated with the *Icyano* index. Moreover, *Icyano* has shown promising results in helping to identify technological and infrastructural improvements in WTPs associated with cyanobacterial blooms in raw water. Additionally, the use of *Icyano* proved to be effective in assisting water resource management in the semi-arid region of Brazil and may have some application in other semi-arid regions of the world and, quite possibly, in other regions as well.

**ACKNOWLEDGEMENTS**

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**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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