Spatial and Temporal Dynamics of Water Quality and Potentially Toxic Cyanobacteria during Drought Conditions in a Mesotrophic Reservoir Ecosystem

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ABSTRACT

A study of potentially toxic cyanobacteria in Ubolratana Reservoir was carried out in 2019, a year when serious drought conditions impacted the mesotrophic reservoir ecosystem. Correlations between environmental factors and cyanobacteria densities were analyzed for a better understanding of stimulating factors and improved management. Sampling was performed four times, during dry (April), early-rainy (June), mid-rainy (July) and late-rainy (August) seasons, and in three zones (riverine, transition, lacustrine). Eight genera of potentially toxic cyanobacteria were recorded: *Cylindrospermopsis, Pseudanabaena, Anabaena, Aphanocapsa, Microcystis, Oscillatoria, Planktolyngbya* and *Merismopedia*. The dominant taxa in all zones were *Cylindrospermopsis, Pseudanabaena,* and *Anabaena,* with maximum densities of 142,110, 82,000, and 43,800 cells·L^{-1}, respectively. The highest total density (220,250 cells·L^{-1}) occurred during the dry season in the transition zone. Densitiy in the riverine zone had a significant negative relationship ($p<0.05$) with total suspended solids (TSS), while density in the transition zone had a highly significant negative relationship ($p<0.01$) with TSS and a significant negative relationship ($p<0.05$) with dissolved inorganic nitrogen (DIN). This study highlights the need to monitor risk from increasing abundance of potentially toxic cyanobacteria in water bodies during continuous drought conditions. Increases of TSS in particular areas during the rainy season may help to decrease the density of potentially toxic cyanobacteria in the reservoir ecosystem. Accordingly, to prevent the potential hazard of toxins to human health, the inflow (with more turbid waters) is of crucial importance for effective management.

Keywords: Drought condition, Environmental factors, Potentially toxic cyanobacteria, Reservoir ecosystem, Risk assessment, Water quality

INTRODUCTION

Cyanobacterial blooms are increasing in frequency worldwide in freshwater ecosystems, especially in reservoirs (Mowe *et al*., 2015; Moura *et al*., 2018). The impacts of these blooms on natural ecosystems include reduction of light intensity, habitat, biodiversity, as well as increased anoxia in the hypolimnion (Schindler *et al*., 2016). In addition, cyanobacteria cause problems in water supply and increased costs of water management due to blooms occurring in reservoirs (Moura *et al*., 2018). In tropical regions, blooms of *Microcystis* (microcystin-producing cyanobacteria) have been recorded in Sri Lanka, Bangladesh, Philippines, Vietnam, Singapore, and Thailand (Mowe *et al*., 2015). Cyanobacterial blooms occur frequently in reservoir ecosystems, and studies have indicated that 25-75 % of these blooms can produce toxins (Chorus, 2001). Such toxins have negative impacts on the reservoir ecosystem, causing mortality of aquatic animals and affecting related trophic levels (Watanabe *et al*.,

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1996; Chorus and Bartram, 1999; Lehman *et al*., 2010). In Thailand, *Microcystis, Cylindrospermopsis, Oscillatoria* and *Pseudanabaeba* are usually observed in recreational reservoirs (Somdee *et al*., 2013). *Microcystis aeruginosa* is the dominant toxic cyanobacterium in Thai reservoirs (Mahakhant *et al*., 1998; Peerapornpisal *et al*., 2002). Previous studies have indicated that levels of microcystin produced by *Microcystis aeruginosa* and *Microcystis wesenbergii* in Thai reservoirs exceeded the concentration prescribed by WHO drinking water guidelines (1 $\mu g \cdot L^{-1}$) (Mahakhant *et al*., 1998; Aroonvilairat *et al*., 2008).

Cyanobacterial blooms are commonly caused by physical factors, including temperature, irradiance, light intensity, turbulence, vertical mixing, flushing rate, retention time, water volume, and water flow (Bouvy *et al*., 2000; Dokulil and Teubner, 2000; Arfi, 2003; Baldia *et al*., 2003; Butterwick *et al*., 2005; Mitrovic *et al*., 2006; Paerl and Otten, 2013; Soares *et al*., 2013; Bittencourt-Oliveira *et al*., 2014; Paerl, 2014), and chemical factors, including nitrogen concentration, phosphorus concentration, and N:P ratio (Carr and Whitton, 1982; Bouvy *et al*., 1999; Rustadi *et al*., 2002; Gondwe *et al*., 2007; Khuantrairong and Traichaiyaporn, 2008; Evtimova and Donohue, 2014; Mowe *et al*., 2015). In addition, many studies have found that climate change has direct and indirect effects on cyanobacterial blooms in reservoirs (Paerl and Huisman, 2008; Elliott, 2012). Climate change may lead to changes in temperature (increased water temperature) and rainfall patterns (nutrient loading, discharge, flushing rate, and drought) (Paerl and Huisman, 2008). Drought conditions in reservoirs may lead to akinete formation in heterocystous cyanobacteria (Briand *et al*., 2002) and can enhance cyanobacterial blooms, especially those of *Cylindrospermopsis raciborskii* (Mowe *et al*., 2015; Moura *et al*., 2018).

In Southeast Asia, 51 drought events were reported from 1999 to 2018 (EM-DAT, 2018). Thailand has continually faced serious hydrological conditions since 2012. Accordingly, many large reservoirs of Thailand have experienced severe drought conditions (Zenkoji *et al*., 2019) including Ubolratana Reservoir, the largest of Northeast Thailand. It is located in Khon Kaen Province, one of the drought disaster areas declared by the Department of Disaster Prevention and Mitigation (Royal Thai Government, 2014). In particular, from 2018-2019, the rainfall in the regions upstream of Ubolratana Reservoir dramatically decreased below the annual average. The dry conditions consequently impacted water storage volume, which fell below the level set as a minimum for sustainable operation of the dam (EGAT, 2019). Drought conditions in Ubolratana Reservoir could, thus, provide an important case study of potentially toxic cyanobacterial blooms and their related causes.

In this study, abundance and generic composition of potentially toxic cyanobacteria were monitored in Ubolratana Reservoir in 2019. Spatial variability in cyanobacterial populations among selected sites of riverine, transition, and lacustrine zones of the reservoir was examined. Relationships between cyanobacterial abundance and several environmental factors were also analyzed. In addition, the reservoir's risk status according to levels of potentially toxic cyanobacteria was also discussed. This research provides practical information for further development of monitoring protocols and management approaches to prevent potential hazards to human health from toxins in reservoir ecosystems.

MATERIALS AND METHODS

Study area

Ubolratana Reservoir is a multi-purpose reservoir located in the northeastern part of Thailand (Figure 1). It has a catchment area of 12,089 km^2, surface area of 410 km^2, and maximum water storage volume of $2,431 \times 10^6$ m^3 (EGAT, 1996; Ingthamjitr *et al*., 2008). It is a relatively shallow water body, with mean depth of 5.5 m. The reservoir receives water from the Phong and Phaniang rivers in the north, and from the Choen River in the south. The main inflow is from the Phong River, with comparatively high turbidity and nutrients due to agricultural activities in the watershed. In the surrounding watershed, there are agricultural uses of the reservoir waters. Gillnet fishing is also commonly observed along the Phong River. Water storage volumes during 2019-2020 were lower than during the previous fifty years (EGAT, 2020). The climate of Northeast Thailand is influenced by two tropical monsoons: the southwest monsoon from May to October (rainy season), and the northeast monsoon from November to February (dry season) (Ingthamjitr *et al*., 2008; EGAT, 2019).

Sampling of cyanobacteria

Sampling was carried out four times in 2019: in April (dry season), June (early-rainy season), July (mid-rainy season) and August (late-rainy season). Survey sites were selected along the Phong River channel in three ecological zones of the reservoir, as defined by Mengchouy and Meksumpun (2019). Two sites (UB1 and UB2) were chosen in the riverine zone, two (UB3 and UB4) in the transition zone, and one (UB5) in the lacustrine zone of the reservoir (Figure 1).

On each sampling occasion, samples of cyanobacteria were collected by bucket from the surface water (0-30 cm water depth). Ten liters of water were filtered through a plankton net (15 µm mesh) and preserved with 4% formaldehyde solution. Cyanobacteria identification was conducted under light microscope (Model CHK/SA0333, Olympus) according to Komárek and Anagnostidis (2005) and Peerapornpisal (2015). Potentially toxic cyanobacterial genera were classified according to Bernard *et al*. (2016). Cyanobacterial genera were counted under light microscope in three sub-samples of 100 µL, and abundance was expressed as cells·L^{-1}.

Water quality parameters

At each sampling location, water temperature was measured at 15 cm below the water surface by multi-parameter probe (YSI Model 650). Transparency was measured with a Secchi disk. Total suspended solids (TSS) and chlorophyll *a* of the water column were also analyzed. Water samples for TSS were passed through GF/C glass-fiber filter, and freeze-dried for the measurement of dry weight per volume of filtered water. Chlorophyll *a* was analyzed by spectrophotometric method (Parsons *et al*., 1984). Dissolved inorganic nitrogen (DIN) and orthophosphate phosphorus (Ortho-P) were analyzed by Skalar's Automatic Nutrient Analyzer (SAN Plus Segmented Flow Analyzer).

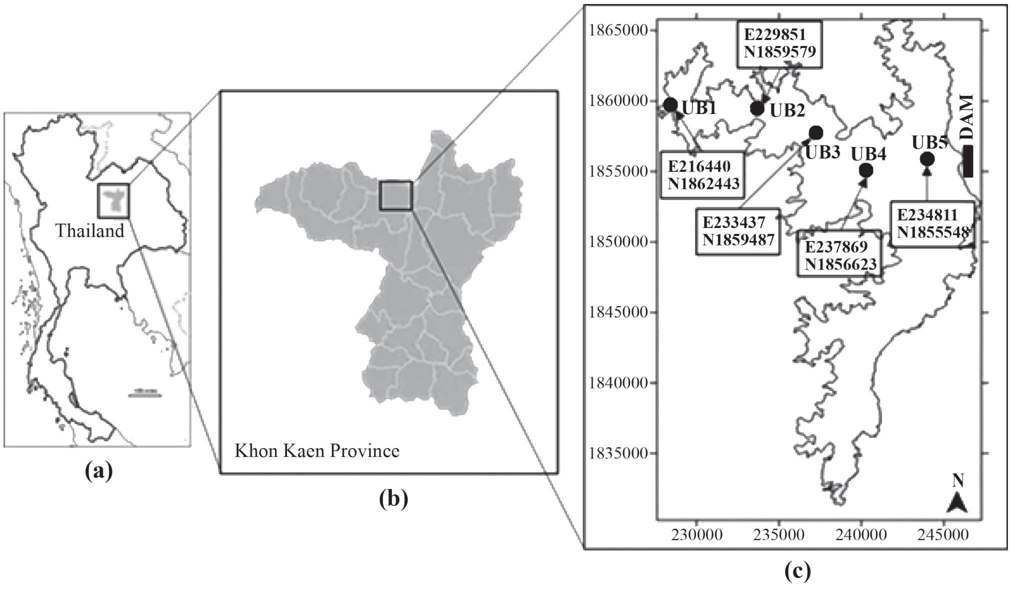

Figure 1. Sampling sites along the Phong River channel in Ubolratana Reservoir, Northeast Thailand. (a) Map of Thailand; (b) Map of Khon Kaen Province; (c) Boundary of Ubolratana Reservoir with locations of the five sampling sites (UB1-UB5).

Hydrological information

Relevant hydrological data (water inflows and storage volume) were acquired from http://watertele.egat.co.th/ubolratana/, developed by the Electricity Generating Authority of Thailand (EGAT, 2019), as it provided the most precise and reliable information. Measurements of inflows ($\times 10^6$ m^3) from the telemetry stations nearest to Phong River sites were used, as well as water storage values ($\times 10^6$ m^3) during 2010-2019.

Data analysis

Physical, chemical and biological data were statistically analyzed using one-way analysis of variance (ANOVA, SPSS Version 27) for determination of spatial and temporal variation. Correlations between density of potentially toxic cyanobacteria and various water parameters were analyzed using Spearman's rank correlation coefficient ($p<0.05$). The risk status (human health effects) of the cyanobacteria was assessed according to the criteria of the WHO's Guidelines for Safe Recreational Water Environments (WHO, 2003).

RESULTS

Changes in hydrological parameters

Monthly inflows to Ubolratana reservoir during the previous 10 years showed an average volume of 56.00×10^6 m^3 (Figure 2; EGAT, 2019). The highest average monthly inflow was found in 2011 (145.00×10^6 m^3), while the lowest was in 2019 (19.50×10^6 m^3). Inflows in 2019 were about four times lower than in 2018 (80.00×10^6 m^3), and were significantly lower than during the previous 10 years (Figure 2a). In terms of seasonal averages during the previous 10 years, inflows during the dry season (April), early-rainy season (June), mid-rainy season (July) and late-rainy season (August) were 24.00, 64.00, 115.50 and 108.50×10^6 m^3, respectively. Generally, the increase of inflows begins during the early-rainy season, but in 2019, the inflow during this period was about three times lower than during the previous 10 years.

The water storage volume of Ubolratana Reservoir during 2010-2019 is shown in Figure 2b. The yearly mean was highest for 2017 ($1,622.50\pm 563.34\times 10^6$ m^3) and lowest for 2019 ($604.50\pm 68.78\times 10^6$ m^3). During 2019, monthly water storage volume gradually decreased to levels lower than the prescribed "minimum storage volume" (580×10^6 m^3) of the reservoir (EGAT, 2019). Very low precipitation and inflows caused the water storage volume to be substantially decreased from normal conditions (TMD, 2019).

Temporal change in water quality parameters

Physical, chemical and biological water quality parameters of Ubolratana Reservoir were investigated during the dry, early-rainy, mid-rainy and late-rainy seasons of 2019 to assess their relationships with cyanobacteria. Water temperature and dissolved inorganic nitrogen (DIN) were significantly different ($p<0.05$) among the four surveyed periods (Table 1). The lowest water temperature (29.60 °C) was found during the mid-rainy season, while highest water temperature (34.60 °C) occurred during early-rainy season. The DIN was lowest (1.69 µM) during the dry season, while the highest DIN (15.87 µM) occurred during the early-rainy season. In this study, orthophosphate levels in all seasons (>0.02 µM) were adequate for growth of cyanobacteria (Carr and Whitton, 1982; Mowe *et al*., 2015). The N:P ratio may have less effect because DIN and orthophosphate are not limiting factors (Paerl *et al*., 2001). In the Ubolratana Reservoir ecosystem, cyanobacteria have been found to represent 80-90 % of the total phytoplankton in terms of density (Muangsringam *et al*., 2019). The highest cyanobacterial density in this study (173,010 cells·L^{-1}) was found during the early-rainy season. Thus, contribution of water temperature and DIN during the early-rainy season could enhance cyanobacterial growth in the reservoir ecosystem.

Spatial variability in water quality parameters

The physical, chemical and biological parameters in 2019 for the three ecological zones are depicted in Table 2. Water temperature was comparatively higher in the transition zone of the reservoir, while DIN was higher (about 15 µM) in the riverine and transition zones. Nevertheless, the results indicated that among zones, water temperature and DIN were not significantly different ($p>0.05$). Transparency, total suspended solids, orthophosphate, N:P ratio and chlorophyll *a* among zones were significantly different ($p<0.05$). Highest water turbidity and orthophosphate was found in the riverine zone (Table 2).

The results reveal that spatial differences in water quality have effects on the blooms of potentially toxic cyanobacteria. Total densities of potentially toxic cyanobacteria were higher in the transition and lacustrine zones (Table 2), where average chlorophyll *a* was higher than 25 $\mu g \cdot L^{-1}$, average TSS was lower than 50 $mg \cdot L^{-1}$, and average transparency was higher than 0.30 m. In contrast, the riverine zone had lower densities of potentially toxic cyanobacteria. There, the average chlorophyll *a* was lower than 2 $\mu g \cdot L^{-1}$. High levels of TSS (>340 $mg \cdot L^{-1}$) and low transparency (<0.30 m) were recorded in the riverine zone, and likely limited the levels of cyanobacteria and chlorophyll *a*.

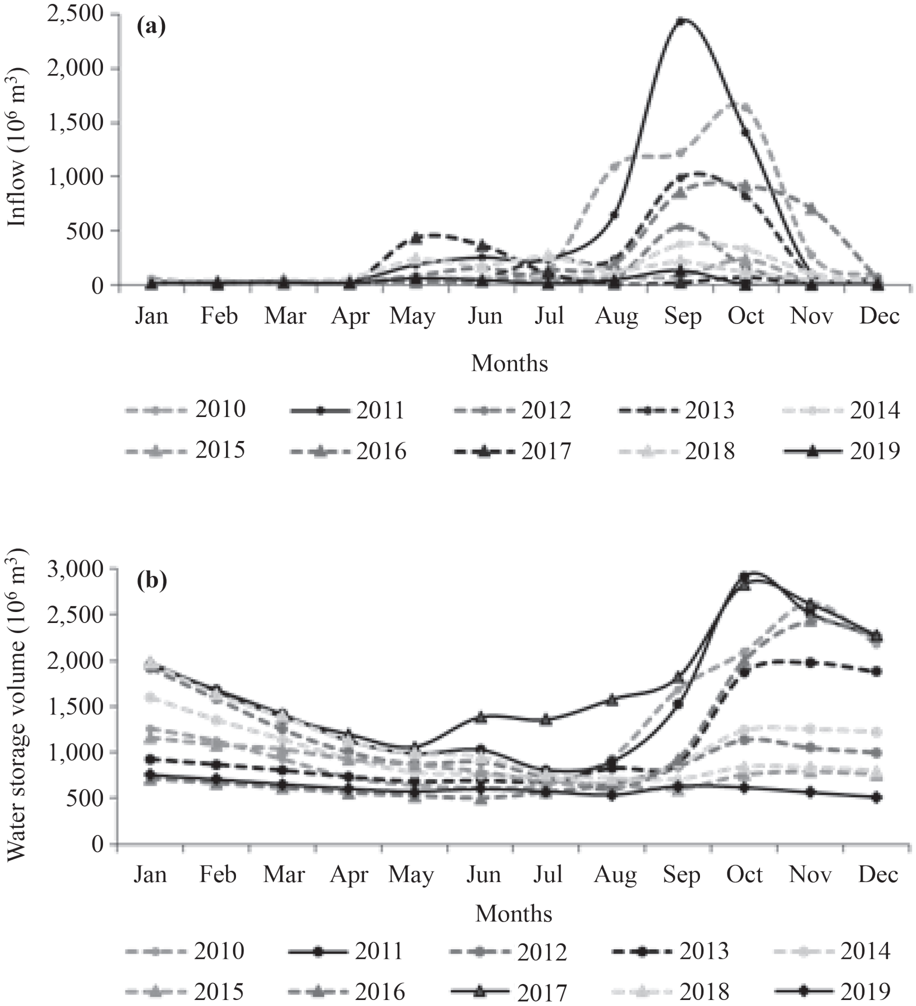

Figure 2. Monthly inflow (a) and water storage volume (b) of Ubolratana Reservoir during 2010-2019 (source: EGAT, 2019).

Table 1. Water quality parameters (water temperature, Temp; transparency, Trans; total suspended solids, TSS; orthophosphate, Ortho-P; dissolved inorganic nitrogen, DIN; N:P ratio; chlorophyll *a*, Chl *a*; and potentially toxic cyanobacteria density, $Density_{Total}$) of Ubolratana Reservoir by season in 2019.

Parameter	Season				ANOVA	
	Dry	Early-rainy	Mid-rainy	Late-rainy		
	Min-Max	Min-Max	Min-Max	Min-Max	F	P
Physical factors						
Temp (°C)	31.40-34.20	31.80-34.60	29.60-33.30	29.70-32.50	4.712	0.015*
Trans (m)	0.05-0.42	0.04-0.80	0.03-0.38	0.10-0.40	0.333	0.802
TSS (mg·L^{-1})	15.24-74.00	16.39-334.00	17.20-715.00	19.20-346.00	0.523	0.672
Chemical factors						
Ortho-P (µM)	0.06-0.45	0.02-0.46	0.05-0.82	0.05-0.24	0.486	0.697
DIN (µM)	1.69-2.66	3.39-15.87	2.39-11.24	2.79 -12.01	3.523	0.039*
N:P ratio	5.77-31.25	24.88-140.24	4.29-221.40	29.97-79.58	1.158	0.357
Biological factors						
Chl *a* (µg·L^{-1})	11.42-52.57	1.34-51.73	1.54-58.52	9.21-73.15	0.560	0.649
$Density_{Total}$ (cells·L^{-1})	8,100-152,500	0-173,010	380-152,880	1,160-90,720	0.297	0.827

Note: * Significant difference ($p<0.05$)

Table 2. Water quality parameters (water temperature, Temp; transparency, Trans; total suspended solids, TSS; orthophosphate, Ortho-P; dissolved inorganic nitrogen, DIN; N:P ratio; chlorophyll *a*, Chl *a*; and potentially toxic cyanobacteria density, $Density_{Total}$) in three ecological zones of Ubolratana Reservoir during 2019.

Parameter	Zone			ANOVA	
	Riverine	Transition	Lacustrine		
	Min-Max	Min-Max	Min-Max	F	P
Physical factors					
Temp (°C)	29.70-34.20	29.60-34.60	30.30-33.30	0.344	0.713
Trans (m)	0.0 -0.15	0.12-0.80	0.30-0.40	9.045	0.002
TSS (mg·L^{-1})	53.20-715.00	19.20-94.80	15.24-19.20	4.192	0.033
Chemical factors					
Ortho-P (µM)	0.12-0.82	0.02-0.19	0.08-0.22	7.351	0.005
DIN (µM)	2.61-15.35	1.79-15.87	1.69-5.41	1.896	0.181
N:P ratio	4.29-68.72	17.62-221.40	21.63-29.97	3.468	0.045
Biological factors					
Chl *a* (µg·L^{-1})	1.34-36.97	2.84-73.15	38.72-58.52	5.928	0.012
$Density_{Total}$ (cells·L^{-1})	0-12,500	4,320-172,890	82,000-173,010	16.705	0.000

Variability in composition and density of potentially toxic cyanobacteria

During 2019, eight genera of potentially toxic cyanobacteria (*Cylindrospermopsis, Pseudanabaena, Anabaena, Aphanocapsa, Microcystis, Oscillatoria, Planktolyngbya* and *Merismopedia*) were identified from Ubolratana Reservoir (Table 3). The highest total density (220,250 cells·L^{-1}) was recorded in the transition zone during the dry season of 2019, while the lowest total density (1,010 cells·L^{-1}) was recorded in the riverine zone during mid-rainy season. Ranges of total densities for the riverine, transition, and lacustrine zones were 1,010-20,600 cells·L^{-1}, 88,680-220,250 cells·L^{-1}, and 82,000-173,010 cells·L^{-1}, respectively. The densities found of the riverine zone were more than 10 times lower than those of the transition and lacustrine zones.

Table 3. Density of potentially toxic cyanobacteria of Ubolratana Reservoir during dry to late-rainy seasons in 2019.

Genera	**Density of potentially toxic cyanobacteria (cells·L^{-1})**			
	Dry season	**Early-rainy season**	**Mid-rainy season**	**Late-rainy season**
Riverine zone				
Cylindrospermopsis	1,250	250	0	2,892
Pseudanabaena	11,450	0	380	1,572
Anabaena	7,900	250	630	3,396
Oscillatoria	0	0	0	880
Aphanocapsa	0	0	0	440
Planktolyngbya	0	2,000	0	0
Total density of riverine zone	20,600	2,500	1,010	9,180
Transition zone				
Cylindrospermopsis	115,900	142,110	74,580	68,080
Pseudanabaena	82,000	11,670	2,880	36,080
Anabaena	8,600	20,370	7,680	13,040
Oscillatoria	12,500	2,295	240	400
Microcystis	0	765	2,880	3,600
Merismopedia	1,250	0	420	2,880
Aphanocapsa	0	0	0	5,440
Total density of transition zone	220,250	177,210	88,680	129,520
Lacustrine zone				
Cylindrospermopsis	95,000	122,640	91,560	45,000
Pseudanabaena	41,250	1,095	30,240	24,500
Anabaena	8,750	43,800	16,800	8,500
Oscillatoria	1,250	0	2,520	500
Microcystis	0	4,380	3,360	0
Merismopedia	6,250	1,095	2,520	3,000
Aphanocapsa	0	0	5,880	0
Planktolyngbya	0	0	0	500
Total density of lacustrine zone	152,500	173,010	152,880	82,000

The most dominant genera in all zones were *Cylindrospermopsis, Pseudanabaena* and *Anabaena* (Table 3). In particular, *Cylindrospermopsis* was very abundant in the transition and lacustrine zones. In those two zones, densities of *Cylindrospermopsis* were highest (142,110 and 122,640 cells·L^{-1}, respectively) during the early-rainy season. By the late-rainy season, the densities had gradually decreased to less than half of the earlier levels (68,080 and 45,000 cells·L^{-1}, respectively). In addition, the genus *Microcystis* was found only in the transition and lacustrine zones of the reservoir.

In the riverine zone, the genera *Pseudanabaena* and *Anabaena* had higher densities than *Cylindrospermopsis*, and their densities were highest (11,450 and 7,900 cells·L^{-1}, respectively) during the dry season. Their densities decreased noticeably during the early to mid-rainy season. The total density of potentially toxic cyanobacteria in the riverine zone was lowest (1,010 cells·L^{-1}) during the mid-rainy season, and about 20 times lower than during the dry season.

Potentially toxic cyanobacteria and related environmental factors

Correlations between environmental factors and density of potentially toxic cyanobacteria are shown in Table 4. In the riverine zone, the density of these bacteria had a significant negative relationship ($p<0.05$) with TSS. In the transition zone, the density had a highly significant negative relationship ($p<0.01$) with TSS and a significant negative relationship ($p<0.05$) with DIN.

Table 4. Correlation coefficients between potentially toxic cyanobacteria density (in riverine, transition, and lacustrine zones) and various environmental factors (water temperature, Temp; transparency, Trans; total suspended solids, TSS; orthophosphate phosphorus, Ortho-P, dissolved inorganic nitrogen, DIN; and N:P ratio, N:P) in Ubolratana Reservoir from April to August 2019.

Factors	Temp	Trans	TSS	DIN	Ortho-P	N:P
$Density_{Riverine}$	0.323^{ns}	0.659^{ns}	-0.762*	-0.643^{ns}	-0.619^{ns}	0.071^{ns}
$Density_{Transition}$	0.599^{ns}	0.119^{ns}	-0.905**	-0.714*	-0.304^{ns}	-0.429^{ns}
$Density_{Lacustrine}$	0.200^{ns}	-0.800^{ns}	-0.400^{ns}	0.400^{ns}	0.632^{ns}	-0.200^{ns}

Note: ^{ns} = No significant difference; * Significant difference ($p<0.05$); ** Highly significant difference ($p<0.01$)

DISCUSSION

The recorded inflows and water storage volumes of Ubolratana Reservoir during 2019 clearly imply severe drought conditions (Figure 2). In 2019, water storage volume was the lowest of the 53 years since the reservoir was constructed and first operated. As a result of very low rainfall (EGAT, 2020), the amount of inflow into the reservoir decreased significantly from previous years. Decreased inflows can impact water quality in the reservoir by causing water stratification and by increasing water temperature and transparency, factors that influence the growth of potentially toxic cyanobacteria (Paerl, 2014). Accordingly, toxic-producing cyanobacteria are found more often during drought conditions (Berg and Sutula, 2015). In addition, a previous study reported that drought conditions of a reservoir could trigger *Cylindrospermopsis* blooms (Bouvy *et al*., 2000).

In this study, eight genera of potentially toxic cyanobacteria were examined from Ubolratana Reservoir (Table 3). These genera can produce toxins such as cylindrospermopsin, microcystin, anatoxin-a, and saxitoxin (Bernard *et al*., 2016). The high density of *Cylindrospermopsis* observed in transition and lacustrine zones of Ubolratana Reservoir during the dry season of 2019 indicates that drought conditions are suitable for the growth of potentially toxic cyanobacteria, in particular the genus *Cylindrospermopsis* (Sprober *et al*., 2003;

Berger *et al*., 2006; Dufour *et al*., 2006; Ghosh *et al*., 2008; Figueredo and Giani, 2009; Mowe *et al*., 2015; Moura *et al*., 2018). Similarly, previous studies have reported that drought conditions and high temperature can favor *Cylindrospermopsis* blooms to a greater degree than *Anabaena* or *Microcystis* (Bouvy *et al*., 2000; Briand *et al*., 2002; Mowe *et al*., 2015).

Our findings differed from those of Muangsringam *et al*. (2019), who carried out a similar study during the period of higher water storage conditions in 2017-2018. Without drought conditions, *Microcystis* was reported to be dominant in Ubolratana Reservoir, whereas in present study, density of *Cylindrospermopsis* (142,110 cells·L^{-1}) was higher than other taxa. The cells of *Cylindrospermopsis*, thus, can grow well during drought conditions (lower inflows, higher temperature, longer retention time, higher nutrient availability and lower nitrogen concentration) due to its ability to fix atmospheric nitrogen (Mowe *et al*., 2015). McGregor and Fabbro (2000) also reported that *Cylindrospermopsis* could grow well when total phosphorus was in the range of 0.05-0.65 µM and water temperature was comparatively high (28-32 °C). In addition, sufficient amounts of DIN within the reservoir ecosystem (Table 2) can also favor the growth of other genera such as non-heterocystous *Oscillatoria* and *Microcystis* (Rippka and Waterbury, 1977; Kallas *et al*., 1985; Rapala *et al*., 1993).

The genus *Microcystis* can occur in transition and lacustrine zones during the rainy season. Such occurrences have been attributed to higher DIN concentrations (Mowe *et al*., 2015). According to the studies of Sekadende *et al*. (2005), Meesukku *et al*. (2007), Onyema (2010) and Sitoki *et al*. (2012), *Microcystis* bloomed in the rainy season due to the high nutrient levels that occur after periods of heavy rainfall. In addition, the genera *Pseudanabaena* and *Anabaena* were more likely to be observed in riverine zones of the reservoir. According to the study of Muangsringam *et al*. (2019), *Pseudanabaena* and *Anabaena* should have higher tolerance for growing in more turbid waters of the riverine zone. *Anabaena* can also be found in high turbidity conditions due to its mechanism to store energy from light (Oliver *et al*., 2012). Furthermore, *Anabaena* biomass was reported to positively correlate with water temperature (Qian *et al*., 2019).

Increased density of potentially toxic cyanobacteria in the reservoir during drought conditions of 2019 indicates that drought conditions provide several suitable factors promoting their growth. Nevertheless, the increases showed a negative relationship with TSS ($p<0.05$, Table 4) due to the reduction of light (Benayache *et al*., 2019). The abundance of potentially toxic cyanobacteria found among sites in this study also indicates that the ecological zonation of the reservoir clearly impacts their density. The most important factors for density in each area of the reservoir appear to be TSS and available nutrients (Table 2). The studies of O'Neil *et al*. (2012), Gobler *et al*. (2016) and Miller *et al*. (2017) similarly showed that turbidity, nutrient level, and light intensity were the most important factors influencing the abundance of potentially toxic cyanobacteria. Thus, the increases of TSS in the riverine zone during the rainy season may help to decrease the density of potentially toxic cyanobacteria in the reservoir ecosystem (Table 4). To prevent the potential hazard of toxins on human health, higher rates of inflow (with more turbid waters) are of crucial importance for effective management.

In addition, blooms of potentially toxic cyanobacteria can affect the food chain, and thus further negative impacts on fisheries, aquaculture, human health and other living organisms (Funari and Testai, 2008; Hilborn and Beasley, 2015; Carmichael and Boyer, 2016). These cyanobacteria possess genes to produce toxin, although they are not always actively releasing the toxin into the environment. Still, we should be aware of the risk and the potential environmental harm caused by blooms of cyanobacteria. The densities of potentially toxic cyanobacteria observed in Ubolratana Reservoir during 2019 (under drought conditions) are considered a "lower-level" of risk of adverse health effects (<20,000,000 cells·L^{-1}), according to criteria for safe recreational water environments (WHO, 2003). However, continued surveillance is recommended. Some other sources of nutrients (i.e. from fish cage cultures) should also be further considered.

CONCLUSION

During the drought conditions in 2019, densities of potentially toxic cyanobacteria in Ubolratana Reservoir ecosystem increased to high levels, with a maximum of 220,250 cells·L^{-1}. The dominant genera observed were *Cylindrospermopsis, Pseudanabaena,* and *Anabaena*. Highest densities of these taxa were found during the dry and early-rainy seasons of the year. In the riverine and transition zones of the reservoir, density of potentially toxic cyanobacteria had significant negative relationships with TSS and DIN. Accordingly, it is possible that increases in density can occur at sites with low TSS and during continuous drought conditions. Conversely, zones with higher TSS (that is, low transparency) are not suitable for the potentially toxic cyanobacteria. Higher TSS conditions can be naturally enhanced by increased inflows to the reservoir ecosystem.

Our findings suggest that there is a need to monitor the level of risk from the increasing abundance of potentially toxic cyanobacteria during drought conditions of the reservoir, in particular in the transition and lacustrine zones. Further studies should assess the impact of flow regime and related management for mitigation of potentially toxic cyanobacteria, in particular the genus *Cylindrospermopsis*. The density of *Cylindrospermopsis* should be monitored and further analyzed in terms of its toxin production potential and health impacts.

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