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12 **Correlations between watershed and reservoir**
13 **characteristics, and algal blooms**
14 **in subtropical reservoirs**
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1 **Abstract**

2 This study examined the correlations between watershed and reservoir characteristics,
3 and water quality parameters related to algal blooms in seven subtropical reservoirs.
4 Analysis of the dissimilarity of physico-chemical parameters resulted in separation of
5 the reservoirs into three main groups: four reservoirs with the highest proportion of
6 agriculture and/or urban land use in their watersheds; two reservoirs with a high
7 proportion of forest cover; and one small reservoir with a relatively pristine watershed
8 was intermediate between the other two groups. All reservoirs were dominated by
9 cyanobacteria, and at times, had species capable of producing toxins. However, the
10 three reservoirs with the lowest percentage forest cover (~50%) had the highest
11 frequency and magnitude of toxic species, principally *Cylindrospermopsis*
12 *raciborskii*. Analysis of dissimilarity of algal species composition resulted in three
13 reservoir groups similar to that for the physico-chemical parameters, with the
14 exception of the reservoir with the highest percentage urban land use being an outlier.
15 Across all reservoirs, percentage forest cover in the watershed, watershed area and
16 reservoir volume were all significantly correlated with algal cell concentrations and
17 total nitrogen (TN), but not with chlorophyll *a* concentrations. Total phosphorus (TP)
18 was only correlated with the proportion forest cover in the watershed, suggesting that
19 reservoir volume and depth were of less importance for TP than for algal cell
20 concentrations or TN. These results suggest that watershed pattern and reservoir
21 characteristics, such as water volume and depth, have a measurable effect on the type
22 of algal blooms in reservoirs.

24 **Keywords**

25 Cyanobacteria, nutrients, reservoir, algal species, watershed

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Introduction

Maintenance of water quality in drinking water reservoirs within required guidelines is a key issue for reservoir managers. Considerable resources are allocated to monitor water quality and trigger responses when water quality deteriorates. This ensures that human and environmental health is not compromised and that treatment plants are not challenged beyond their capabilities. One of the key water quality parameters of concern is cyanobacterial blooms. Depending on the dominant species, blooms may create low oxygen conditions, taste and odour problems, or produce toxins harmful to humans and animals (Oliver and Ganf 2000)

Anthropogenic modification of reservoir watersheds, such as agriculture, increases nutrient and suspended solids inputs during inflow events. Broudscale cropping or grazing can encompass a large proportion of the watershed and there is evidence of increased nutrients and suspended solids in receiving waters as a result (Ulrich 1997; Harris 2001; Knoll et al. 2003). A study of American water suppliers found that 50 to 55% of the variation in treatment costs for reservoir water can be explained by the percentage natural vegetation i.e. forest cover in the watershed. More specifically they found that with every 10% increase in forest cover (up to 60% cover), water treatment costs were reduced by approximately 20% (Ernst 2004).

However, watershed inputs, particularly nutrients, are not the only driver of algal growth. Reservoirs have created an artificial environment conducive to algal growth, and particularly cyanobacteria, with calm waters, low light attenuation and a relatively long residence time. Additionally reservoirs can be a trap for watershed nutrients,

1 which may be processed into more bioavailable forms in the water column and
2 sediment prior to utilization by algae within the system. The longer the residence
3 time, and the more anoxic the bottom waters, the more likely this is to happen. In
4 subtropical and tropical regions this problem is exacerbated by warm summers
5 stimulating rapid algal growth, peaks in nutrient inputs from large inflow events, and
6 infrequent flushing (Jones and Poplawski 1998). Therefore factors such as residence
7 time, light availability, mixing, and water depth can be expected to affect algal
8 growth.

9

10 This study involved an inter-reservoir comparison of both reservoir and watershed
11 characteristics that may be promoting algal blooms in subtropical reservoirs.

12

13 **Materials and Methods**

14 The study involved seven drinking water reservoirs in subtropical southeast
15 Queensland, Australia (Fig. 1). The full supply volumes ranged from 9,280 to
16 1,165,000 ML with watershed areas ranging from 5,600 to 571,000 ha (Table 1).
17 Leslie Harrison reservoir was the shallowest with a mean depth of 5.3 m while Hinze
18 reservoir was the deepest, 17.8 m. The water residence time, in years, was calculated
19 as the total volume divided by the mean yearly water release volumes. Data was not
20 available for Manchester reservoir. North Pine and Manchester reservoirs had a
21 destratification unit operating throughout the period of the study (Antenucci et al.,
22 2005; Burford & O'Donohue 2006).

23

24 Manchester reservoir had the most pristine watershed with close to 100% forest (Fig.
25 2). The other extreme was Wivenhoe Reservoir which had approximately 50%

1 agricultural land, much of this being used for cattle grazing. Leslie Harrison
2 Reservoir had the highest proportion of urban land, although most of this was low-
3 density rural properties.

4

5 The study involved sampling on 4 occasions (4-8 October 2004, 13-17 December
6 2004, 7-11 February 2005, 11-15 April 2005). All seven reservoirs (Leslie Harrison
7 (LH), Little Nerang (LN), Hinze (HZ), North Pine (NPD), Somerset (SOM),
8 Wivenhoe (WIV), Manchester (MAN)) were sampled on each occasion. The same
9 sampling equipment and protocol was used throughout the study. Two sites were
10 sampled in each reservoir, one near the reservoir wall, the other upstream near the
11 inflow from the largest river. The upstream site was approximately 1 km upstream in
12 the case of Manchester, Leslie Harrison and Little Nerang reservoirs, while Hinze
13 was 2 km, North Pine and Somerset were 5 to 6 km and Wivenhoe was 12 km.
14 Surface water was sampled at each site using a PVC pipe to obtain a top 3 m depth-
15 integrated sample. Water was then poured into a clean bucket. Bottom water (a few
16 metres from the bottom) was sampled at each site using a van Dorn sampler and
17 poured into a clean bucket.

18

19 Replicate subsamples from the surface and bottom at each site were taken from the
20 buckets for TN and TP analysis and stored on ice until frozen in the laboratory.
21 Replicate subsamples for chlorophyll *a* analysis (surface and bottom) were also taken
22 by filtering known volumes of water into GF/F glass fibre filters, and storing the
23 filters on ice until frozen in the laboratory. Surface (only) subsamples were taken for
24 total algal counts, and taste and odour compounds (geosmin, methylisoborneol
25 (MIB)). For algal counts, 0.6 mL Lugol's solution was added as a fixative, while for

geosmin and MIB, subsamples were used to completely fill 20 mL dark glass bottles and stored on ice. On one sampling occasion, February 2005, subsamples from the surface and bottom were also filtered through 0.47 μm (pore size) membrane filters for dissolved nutrient (oxides of nitrogen, phosphate, ammonium, dissolved organic carbon) analyses.

Physical parameters were also profiled through the water column, at 1m depth intervals, using a multi-parameter instrument (Sonde) (temperature, conductivity, pH, fluorescence, oxygen, turbidity). The surface mixed layer (SML) depth was calculated based on a temperature difference between adjacent depths of $>0.25^{\circ}\text{C}$. Secchi disc readings were obtained at each site. On the final sampling occasion, light profiles were also measured through the water column using a photosynthetically active radiation (PAR) sensor. The relationship between Secchi disc and euphotic depth (1% surface light) calculated from the light sensor was determined to be:

$$\text{Euphotic depth (m)} = \text{Secchi depth (m)} * 1.8 \ (P < 0.0005)$$

The value of 1.8 is consistent with literature values (Chapra 1997).

All analyses were conducted at a laboratory accredited by the Australian National Association of Testing Authorities (NATA). TN, TP, filterable reactive phosphorus (phosphate), ammonium and oxides of nitrogen were analysed using standard colorimetric methods (American Public Health Association, 1995). Filters for chlorophyll *a* analysis were extracted in acetone and measured spectrophotometrically (American Public Health Association 1995). Geosmin and MIB were analysed using a purge-and-trap gas chromatograph-mass spectrometry

1 technique. The detection limit was 4 ng L^{-1} and the analytical precision was
2 determined to $\pm 3\%$.

3

4 In the laboratory, samples were identified to species level where possible under
5 phase-contrast microscopy. Cells were counted by direct counting of fixed samples
6 using a Sedgewick Rafter counting chamber. A minimum of 30 fields and 100 algal
7 units were counted to yield a final result of $\pm 20\%$ of the true cell concentration
8 (Lund et al. 1958). Biovolume estimates for species with cell concentrations > 5000
9 ml^{-1} was summed to calculate the total biovolume in each reservoir for each sampling
10 occasion.

11

12 Rainfall data was obtained from the Bureau of Meteorology. Statistical analysis of
13 water quality, reservoir and watershed data was conducted using SAS and PRIMER
14 software. Prior to analyses, data was tested for normality to comply with
15 assumptions of statistical analyses.

16

17 All multivariate statistical analyses were performed with PRIMER 5 software
18 (Plymouth, UK, <http://www.primer-e.com/>). Multidimensional scaling (MDS) plots
19 were generated for water quality data, i.e. TN, TP, dissolved oxygen, turbidity, Secchi
20 depth and chlorophyll *a*, as well as algal species composition data. Analysis of
21 similarities between reservoirs was conducted (ANOSIM). Mantel's Test was
22 performed to correlate the watershed and reservoir characteristics (size of watershed,
23 land use proportions, rainfall between sampling occasions, reservoir volume,
24 $((\text{watershed area} * \text{residence time}) / \text{reservoir volume}))$ with the water quality data for

1 each sampling period, and to test for relationships between multivariate patterns
 2 (BIOENV, RELATE).
 3
 4 Univariate analyses were performed with SAS software (<http://www.sas.com/>) to
 5 determine the effect of (a) watershed area, (b) land use (%forest, agriculture), (c)
 6 reservoir volume, (d) reservoir mean depth, (e) (watershed area * residence time)/
 7 reservoir volume and (f) rainfall (between sampling periods) on algal cell
 8 concentrations, chlorophyll *a*, TN and TP across the reservoirs. Only statistically
 9 significant correlations are shown.

10

11 **Results**

12 Algal cell concentrations were highest in North Pine, Somerset and Wivenhoe
 13 reservoirs on all four sampling occasions (Fig. 3). Little Nerang also had a high cell
 14 concentration in October 2004. The algal community in all reservoirs was comprised
 15 almost entirely of cyanobacteria throughout the study.

16

17 The dominant cyanobacteria were a range of coccoid, colony-forming genera
 18 (*Aphanocapsa*, *Aphanothece*, *Cyanodictyon*, *Microcystis*, *Synechococcus* and
 19 *Merismopedia*) as well as the solitary filamentous genera (*Cylindrospermopsis*,
 20 *Planktolyngbya* and *Pseudanabaena*) (Table 2). *Aphanocapsa* was numerically the
 21 most common across the reservoirs and Somerset reservoir had the highest cell
 22 concentrations. Potentially toxic cyanobacteria were occasionally present in all
 23 reservoirs, with *Cylindrospermopsis raciborskii* being the most prevalent in North
 24 Pine, Somerset and Wivenhoe reservoirs, and *Microcystis aeruginosa* in Leslie
 25 Harrison (Table 3). *Anabaena circinalis* and *Aphanizomenon ovalisporum* were also

present in some reservoirs at relatively low concentrations.

TN, TP and chlorophyll *a* concentrations varied substantially between reservoirs, with mean reservoir concentrations ranging from 0.381 to 0.620 mg L⁻¹, 0.018 to 0.033 mg L⁻¹ and 7.06 to 11.88 µg L⁻¹ for TN, TP and chlorophyll *a* respectively (Table 4). Molar TN:TP ratios were all substantial higher (>39) than Redfield (1958) ratios (16:1).

Dissolved nutrient concentrations were only measured in February 2005, but there were distinct higher concentrations of ammonium in bottom waters compared with surface waters (Fig. 4). In some reservoirs, oxides of nitrogen were also higher in bottom waters. In the case of phosphate, Somerset and Wivenhoe reservoirs had substantially higher concentrations in bottom waters than that found in other reservoirs. Concentrations of all nutrients were often undetectable in surface waters. Consistent with the TN:TP ratios, dissolved inorganic N:P ratios of bottom waters were always substantially higher than Redfield (1958) ratios.

The mean surface water temperature at the time of sampling was similar across the seven reservoirs but other physico-chemical parameters varied substantially between reservoirs and sampling occasions (Table 5). Bottom oxygen was generally lower in the deepest reservoir, Hinze, while conductivity was highest in Wivenhoe, and Manchester had the lowest light attenuation. The SML was deepest in North Pine Dam, which had an artificial destratification system operating. All reservoirs had the taste and odour compounds, geosmin and MIB present in detectable levels (> 4 ng L⁻¹) at some time during the study, but these were not significantly correlated with

1 either total cyanobacterial cell concentrations or cell concentrations of genera
2 capable of producing geosmin and/or MIB.

3

4 Most rain fell between the October and December 2004 sampling occasions with
5 little rainfall throughout the rest of the summer wet season (Fig. 5). The only
6 reservoirs with increased dam levels between October and December, as a result of
7 the rainfall, were Hinze, Little Nerang and Leslie Harrison. The only other increase
8 in dam level was in Manchester between December 2004 and February 2005. Water
9 levels declined in some reservoirs as a result of both water abstraction and
10 evaporation.

11

12 Multidimensional scaling (MDS) plots of dissimilarity in water quality parameters
13 (TN, TP, turbidity, Secchi depth, bottom oxygen, chlorophyll *a*) across all the
14 reservoirs, showed that North Pine, Somerset, Wivenhoe and Leslie Harrison were
15 closely grouped, with Hinze and Little Nerang distinctly different, and Manchester
16 intermediate (Fig. 6). All reservoirs were statistically different from each other
17 ($P < 0.05$) with the exception of Hinze and Little Nerang, North Pine and Somerset,
18 and Leslie Harrison and Somerset.

19

20 An MDS plot of algal species composition was also compared across reservoirs:
21 Hinze and Little Nerang grouped, while North Pine, Somerset and Wivenhoe also
22 grouped (Fig. 7). Leslie Harrison was distinctly different from all other reservoirs.
23 MDS plots of algal species composition over time showed that October 2004, which
24 was pre-rainfall and early in the summer, was significantly different ($P < 0.05$) from
25 the other sampling occasions (Fig. 8).

1
 2 The multivariate water quality parameters (TN, TP, turbidity, Secchi depth, bottom
 3 oxygen, chlorophyll *a*) were significantly correlated ($P < 0.01$) with percentage
 4 agriculture, forest in the watershed and rainfall, but not with reservoir volume or
 5 watershed area, or (watershed area * residence time)/ reservoir volume. Algal
 6 species composition was significantly correlated ($P < 0.01$) with rainfall, reservoir
 7 volume, watershed size, percentage agriculture, and forest in the watershed, but not
 8 watershed area or (watershed area * residence time)/ reservoir volume.

9
 10 Univariate analysis of key water quality parameters, i.e. algal cell concentrations, TN
 11 and TP, were all significantly correlated ($P < 0.05$) with the percentage forest in the
 12 watershed (Table 6). Algal cell was also significantly correlated with watershed area
 13 and the watershed*residence time/reservoir factor. Chlorophyll *a* was only
 14 significantly correlated with rainfall. There was only a weak but significant
 15 correlation ($P < 0.05$) between chlorophyll *a* and algal cell concentrations ($R^2 = 0.13$),
 16 with a more highly significant ($P < 0.005$) correlation between chlorophyll *a* and total
 17 algal biovolumes for all cells > 5000 cells mL^{-1} ($R^2 = 0.33$).

18

19 **Discussion**

20 This study has shown a correlation between watershed land use and algal cell, TN and
 21 TP concentrations in seven subtropical reservoirs. This is presumably due to the
 22 increased nutrient loads from anthropogenically modified watersheds entering the
 23 reservoirs and is consistent with findings in temperate reservoirs and lakes. A study
 24 of thirty lake watersheds in Connecticut, USA, also found that the proportion forest
 25 cover, urban and agricultural land were significantly correlated with TN and TP in the

1 corresponding lakes (Field et al., 1996).

2

3 Similarly, a study of twelve reservoirs in Ohio, USA, found that watershed land use
4 correlated with primary production, TP and chlorophyll but there was a well defined
5 upper limit to the effect of land use on these three parameters (Knoll et al., 2003).

6 However, the correlation was greatly improved when land use was combined with the
7 ratio of watershed land area to reservoir volume, and the ratio of cropland area to
8 number of livestock. Our study also found that the ratio of watershed area * residence
9 time/reservoir volume was significantly correlated with algal cell concentrations.

10 This is not surprising as a larger watershed area is likely to contribute more nutrients
11 per volume of reservoir, than a smaller watershed.

12

13 In our study, the reservoirs with the highest TN and TP also had the highest incidence
14 of toxic cyanobacteria, in particular *Cylindrospermopsis raciborskii*. This species
15 typically dominates many subtropical and tropical reservoirs in Australia during
16 summer months (McGregor and Fabbro 2000, Burford and O'Donohue 2006). In a
17 study of 47 reservoirs and weirs in subtropical and tropical Australia, McGregor and
18 Fabbro (2000) found the highest concentrations of *C. raciborskii* in systems with TP
19 in the mesotrophic to hypertrophic range, i.e. 13 to 368 $\mu\text{g L}^{-1}$. All the reservoirs in
20 our study had TP concentrations in this range.

21

22 Short term studies of watershed effects on water quality may mask the long term
23 effects of climate. Paleolimnological studies provide a means to differentiate climate
24 versus land use effects. A paleolimnological study in a Canadian lake found that land
25 use parameters (rural and urban) were stronger determinants of increased algal

1 biomass, and nuisance cyanobacterial species, than climatic factors (Hall et al., 1999).

2 In addition, paleolimnological studies in Florida lakes have also shown that

3 cyanobacterial proliferation increased recently and abruptly in response to

4 eutrophication (Riedinger-Whitmore et al., 2005).

5

6 In addition to the increases in the total nutrient loads with watershed modification, the

7 quality of the nutrients may also change. Forested watersheds typically export more

8 dissolved organic nitrogen than altered watersheds (Harris 2001). Since DON is

9 generally less bioavailable, it is less likely to contribute directly to algal growth. The

10 nitrogen:phosphorus ratio may also be affected. A study of 113 lakes in Iowa, USA,

11 found that lakes in watershed with large areas of pasturelands had low

12 nitrogen:phosphorus ratios, which are usually associated with cyanobacterial blooms

13 (Arbuckle and Downing 2001). However in our study, the nitrogen:phosphorus ratios

14 in all reservoirs were higher than Redfield (1958) ratios suggesting that nitrogen was

15 present in excess, relative to phosphorus, despite the dominance of cyanobacteria.

16 Australian reservoirs typically act as phosphorus sinks when retention times are more

17 than one year (Harris 2001), which is the case in the subtropical reservoirs in this

18 study. A study of one of these reservoirs, North Pine reservoir, found that

19 cyanobacteria capable of fixing nitrogen dominated despite the high dissolved

20 inorganic nitrogen concentrations, and indeed were very effective at utilizing these

21 sources (Burford et al., 2006). Phosphorus is more likely to be bound to particles in

22 the sediment than nitrogen.

23

24 This study found that some reservoir characteristics, i.e. reservoir volume, were also

25 significantly correlated with algal cell concentrations in reservoirs, while reservoir

1 depth correlated negatively with TN concentration. The correlation between reservoir
2 depth and TN may be the result of remineralized N being more readily mixed into the
3 epilimnion in shallower waters. The higher concentrations of ammonium in bottom
4 waters compared to surface waters (measured in February 2005 only) confirms the
5 importance of sediment remineralization in generating ammonium. The bottom
6 waters in some reservoirs also had high concentrations of oxides of nitrogen,
7 suggesting that nitrification was also a significant process in the more oxic waters
8 near the sediment surface. Previous long-term studies in three of the reservoirs in this
9 study, North Pine, Somerset and Wivenhoe, have also shown that higher dissolved
10 inorganic nitrogen concentrations occur in bottom waters, indicative of
11 remineralization (Burford and O'Donohue 2006). However, this needs to be coupled
12 with information about the mixing regime in the reservoir to determine how available
13 these nutrients are to algal growth. The SML depths measured in this study were
14 highly variable between reservoirs with the smallest reservoirs having the shallowest
15 SML, and larger reservoirs, and those with destratification units having the deepest
16 SML.

17
18 In contrast, the relatively low TP and phosphate concentrations in the reservoirs in
19 this study suggest that either the rate of sediment remineralization of phosphorus was
20 low compared with nitrogen, or alternatively that phosphorus loads entering the
21 reservoir were low. Further work is needed to determine the relative importance of
22 these processes. However, reservoir depth in two Portuguese reservoirs was found to
23 be a better determinant of trophic status than nutrient loading from the watershed
24 (Matias and Boavida 2005). Similarly, in a study of 86 lakes in Ontario, Canada, TN
25 and TP did not correlate with lake order in the watershed, possibly due to internal

processes such as high rates of nutrient retention in sediments or removal via denitrification (Quinlan et al., 2003).

The water quality status of reservoirs can be classified using a wide range of criteria such as algal blooms, nutrient concentrations, and other contaminant loads. The United States Environmental Protection Agency (US EPA) had developed regional criteria for comparing reservoirs based on a comparison with unimpacted reference reservoirs (US EPA 2002). This study found that nutrients contribute to 50% of reported water quality problems in lakes, reservoirs and ponds. Agriculture was the most widespread source of impact (>40%). In order to undertake a similar assessment in subtropical reservoirs, more water quality and watershed information for a larger number of reservoirs is needed. However this study has shown that it is possible to differentiate reservoirs with respect to a range of both water quality parameters and reservoir land use.

Conclusions

In conclusion, this inter-reservoir study has shown that:

- There was a distinct grouping of reservoirs, based on their water quality parameters, with watershed land use
- The proportion of forest cover in the watershed was significantly correlated with algal cell concentrations, as well as TN and TP in the reservoirs suggesting that a shift from 100 to 50% forest has had a substantial effect on water quality.
- Reservoirs with the highest nutrient concentrations also had the highest frequency and magnitude of toxic algal species.

- 1 • Watershed area and the ratio of watershed area * residence time/reservoir
2 volume were significantly correlated with algal cell concentrations,
3 suggesting that reservoir characteristics cannot be ignored.
4

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1 **Figure Legend**

2

3 Figure 1: Map of the study area showing the location of the seven reservoirs in
4 southeast Queensland, Australia. Filled circles in reservoirs show sampling sites.

5

6 Figure 2: Percentage watershed land use for the seven reservoirs in the study, with
7 increasing watershed area.

8

9 Figure 3: Cell concentrations (cyanobacteria, other algae, cells mL⁻¹) for the four
10 sampling occasions in the seven reservoirs. HZ = Hinze, LH = Leslie Harrison, LN =
11 Little Nerang, MAN = Manchester, NPD = North Pine, SOM = Somerset, WIV =
12 Wivenhoe.

13

14 Figure 4: Mean dissolved nutrient concentrations (+ SD, mg L⁻¹, n=3) on the surface
15 and bottom in the seven reservoirs. Only measured in February 2006. nd = < 0.002
16 mg L⁻¹

17

18 Figure 5: (a): Percentage change in the water level in the seven reservoirs between
19 sampling occasions, and (b) rainfall between sampling occasions in the seven
20 reservoirs.

21

22 Figure 6: MDS of the water quality parameters (TN, TP, turbidity, Secchi depth,
23 oxygen, chlorophyll *a* concentrations) in the seven reservoirs across the four sampling
24 occasions.

25

1 Figure 7: MDS of algal species composition in the seven reservoirs across the four
2 sampling occasions.

3

4 Figure 8: MDS of the algal species composition in the four sampling occasions across
5 the seven reservoirs.

6

Table 1: Comparison of the watershed area, reservoir capacity and mean depth of the seven reservoirs in the study. *At time of study and for some years before no drawdown was occurring.

Parameter	Little Nerang	Manchester	Hinze	Leslie Harrison	North Pine	Somerset	Wivenhoe
Watershed Area (ha)	5,600	7,400	14,600	11,700	34,700	134,200	571,600
Reservoir capacity @ FSL (ML)	9,280	26,000	163,500	24,800	215,000	380,000	1,165,000
Mean Depth (m)	16.7	~12	17.8	5.3	9.9	9.0	10.8
Water residence time (y)	1.5	*	3	4.5	2	10	20

Table 2: Mean ($\pm$ SD) algal cell concentrations (cells mL⁻¹) for all genera with mean cell concentrations > 10,000 cells mL⁻¹ across the seven reservoirs. *Toxic species. Empty cells have cell concentrations less than 5 cells mL⁻¹.

Genera	Hinze	Leslie Harrison	Little Nerang	Manchester	North Pine	Somerset	Wivenhoe
<i>Planktolyngbya</i>						149,000 (148,000)	34,000 (41,000)
<i>Cyanodictyon</i>			91,000 (140,000)		21,000 (31,000)	13,000 (16,000)	
<i>Aphanocapsa</i>	14,000 (7,000)			13,000 (8,000)	47,000 (35,000)	72,000 (53,000)	59,000 (59,000)
<i>Synechococcus</i>			40,000 (35,000)				
<i>Cylindrospermopsis raciborskii</i> *					30,000 (30,000)	10,000 (16,000)	
<i>Merismopedia</i>						14,000 (19,000)	26,000 (31,000)
<i>Aphanothece</i>					15,000 (14,000)	13,000 (15,000)	14,000 (10,000)
<i>Microcystis aeruginosa</i> *		14,000 (16,000)					
<i>Pseudanabaena</i>							11,000 (10,000)
Total cell concentrations	66,000 (17,000)	54,000 (41,000)	227,000 (238,000)	101,000 (30,000)	328,000 (32,000)	565,000 (229,000)	360,000 (155,000)

Table 3: Mean detectable cell concentrations (cells mL⁻¹) of toxic cyanobacterial species across the seven reservoirs and four sampling occasions. Empty cells have cell concentrations less than 5 cells mL⁻¹.

Species	Date	Hinze	Leslie Harrison	Little Nerang	Manchester	North Pine	Somerset	Wivenhoe
<i>Microcystis aeruginosa</i>	Oct'04		40			1,330		
	Dec'04	3,010	35,880			100		
	Feb'05	10	5,940		3,250			
	Apr'05	100	7,000	6,380				
<i>Cylindrospermopsis raciborskii</i>	Oct'04					340		
	Dec'04					17,770	6,590	2,630
	Feb'05				1,500	63,390	22,330	18,380
	Apr'05				9,570	38,090	1,300	2,300
<i>Anabaena circinalis</i>	Oct'04	720						
	Dec'04	2,760				140	710	200
	Feb'05	1,410						
	Apr'05	110						
<i>Aphanizomenon ovalisporum</i>	Oct'04							
	Dec'04							
	Feb'05						320	1,530
	Apr'05							

Table 4: Mean ($\pm$ SD) of TN, TP (mg L^{-1}), TN:TP molar ratios and chlorophyll *a* ($\mu\text{g L}^{-1}$) across surface and bottom waters, sampling occasions, and within-reservoir sites for the seven reservoirs in the study.

Reservoir	TN mg L^{-1}	TP mg L^{-1}	Molar TN:TP ratio	Chlorophyll <i>a</i> $\mu\text{g L}^{-1}$
Hinze	0.401 (0.104)	0.030 (0.029)	45 (19)	7.06 (2.59)
Leslie Harrison	0.620 (0.109)	0.031 (0.004)	44 (5)	9.25 (5.29)
Little Nerang	0.381 (0.160)	0.024 (0.016)	39 (14)	8.81 (5.17)
Manchester	0.414 (0.063)	0.015 (0.003)	64 (18)	7.13 (3.74)
North Pine	0.517 (0.063)	0.018 (0.005)	66 (16)	11.88 (4.15)
Somerset	0.536 (0.067)	0.033 (0.018)	42 (14)	11.06 (5.12)
Wivenhoe	0.478 (0.066)	0.022 (0.010)	54 (16)	8.50 (3.50)

Table 5: Mean ($\pm$ SD) of a range of water quality parameters across depths, sampling occasions, and within-reservoir sites for the seven reservoirs in the study. DO = dissolved oxygen, surf temp = surface temperature, Cond = conductivity, SML = surface mixed layer, MIB = methylisoborneol.

Reservoir	Bottom DO (mg L⁻¹)	Surf temp (°C)	pH	Turbidity (NTU)	Spec. Cond. (uS cm⁻¹)	Secchi depth (m)	SML (m)	MIB (ng L⁻¹)	Geosmin ng L⁻¹
Hinze	0.24 (0.21)	25.81 (2.64)	6.80 (0.74)	2.12 (2.92)	70 (10)	1.8 (0.4)	3.9 (2.7)	2.3 (3.3)	1.7 (2.5)
Leslie Harrison	0.77 (1.30)	26.22 (3.06)	6.79 (0.57)	2.69 (3.98)	104 (8)	2.5 (0.4)	4.4 (5.5)	6.0 (4.3)	16.3 (13.9)
Little Nerang	4.11 (2.06)	26.28 (3.04)	6.99 (0.35)	9.15 (5.70)	212 (12)	1.2 (0.2)	1.4 (0.7)	3.3 (4.6)	3.1 (4.4)
Manchester	0.50 (0.72)	26.95 (2.98)	7.00 (0.41)	1.14 (2.31)	149 (14)	3.0 (0.3)	1.0 (0.5)	2.5 (3.5)	1.9 (2.7)
North Pine	3.29 (2.43)	25.17 (2.52)	7.78 (0.43)	2.22 (1.37)	222 (5)	1.7 (0.4)	10.1 (6.7)	5.5 (4.1)	5.1 (3.6)
Somerset	3.17 (2.05)	25.76 (2.87)	7.63 (0.56)	3.01 (2.72)	262 (17)	1.3 (0.3)	6.7 (7.7)	1.9 (2.7)	6.0 (4.9)
Wivenhoe	2.62 (3.24)	26.15 (2.41)	7.77 (0.44)	2.33 (1.73)	374 (8)	1.8 (0.4)	7.3 (9.3)	1.8 (2.5)	2.1 (2.9)

Table 6: Significant correlations between water quality variables (TN, TP, total algal cell concentrations, chlorophyll *a*) and a range of watershed and reservoir characteristics. ⁺Manchester reservoir not included in analysis as residence time is unknown.

Variable	Correlated with	N	Rho	p-value
Total algal cell concentrations	% Forest	56	-0.421	<0.005
	Watershed area		0.527	<0.0001
	Reservoir volume		0.405	<0.005
	Watershed area*residence time/reservoir volume ⁺	48	0.430	<0.005
Chlorophyll <i>a</i>	Rainfall	56	0.371	<0.0001
TN	% Forest	56	-0.550	<0.0001
	% Agriculture		0.500	<0.0001
	Watershed area		0.364	<0.01
	Depth		-0.715	<0.0001
TP	% Forest	56	-0.383	<0.005
	% Agriculture		0.286	<0.05

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig 8