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Published
2007

Journal Title
Water Research

DOI
https://doi.org/10.1016/j.watres.2007.05.053

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Correlations between watershed and reservoir characteristics, and algal blooms in subtropical reservoirs

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

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

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

**Materials and Methods**

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

Manchester reservoir had the most pristine watershed with close to 100% forest (Fig. 2). The other extreme was Wivenhoe Reservoir which had approximately 50%
agricultural land, much of this being used for cattle grazing. Leslie Harrison Reservoir had the highest proportion of urban land, although most of this was low-density rural properties.

The study involved sampling on 4 occasions (4-8 October 2004, 13-17 December 2004, 7-11 February 2005, 11-15 April 2005). All seven reservoirs (Leslie Harrison (LH), Little Nerang (LN), Hinze (HZ), North Pine (NPD), Somerset (SOM), Wivenhoe (WIV), Manchester (MAN)) were sampled on each occasion. The same sampling equipment and protocol was used throughout the study. Two sites were sampled in each reservoir, one near the reservoir wall, the other upstream near the inflow from the largest river. The upstream site was approximately 1 km upstream in the case of Manchester, Leslie Harrison and Little Nerang reservoirs, while Hinze was 2 km, North Pine and Somerset were 5 to 6 km and Wivenhoe was 12 km.

Surface water was sampled at each site using a PVC pipe to obtain a top 3 m depth-integrated sample. Water was then poured into a clean bucket. Bottom water (a few metres from the bottom) was sampled at each site using a van Dorn sampler and poured into a clean bucket.

Replicate subsamples from the surface and bottom at each site were taken from the buckets for TN and TP analysis and stored on ice until frozen in the laboratory. Replicate subsamples for chlorophyll \( a \) analysis (surface and bottom) were also taken by filtering known volumes of water into GF/F glass fibre filters, and storing the filters on ice until frozen in the laboratory. Surface (only) subsamples were taken for total algal counts, and taste and odour compounds (geosmin, methylisoborneol (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°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:

\[ \text{Euphotic depth (m)} = \text{Secchi depth (m)} \times 1.8 \quad (P < 0.0005) \]

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
technique. The detection limit was 4 ng L\(^{-1}\) and the analytical precision was determined to ± 3%.

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

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

All multivariate statistical analyses were performed with PRIMER 5 software (Plymouth, UK, http://www.primer-e.com/). Multidimensional scaling (MDS) plots were generated for water quality data, i.e. TN, TP, dissolved oxygen, turbidity, Secchi depth and chlorophyll \(a\), as well as algal species composition data. Analysis of similarities between reservoirs was conducted (ANOSIM). Mantel’s Test was performed to correlate the watershed and reservoir characteristics (size of watershed, land use proportions, rainfall between sampling occasions, reservoir volume, ((watershed area * residence time)/ reservoir volume)) with the water quality data for
each sampling period, and to test for relationships between multivariate patterns (BIOENV, RELATE).

Univariate analyses were performed with SAS software (http://www.sas.com/) to determine the effect of (a) watershed area, (b) land use (%forest, agriculture), (c) reservoir volume, (d) reservoir mean depth, (e) (watershed area * residence time)/reservoir volume and (f) rainfall (between sampling periods) on algal cell concentrations, chlorophyll \(a\), TN and TP across the reservoirs. Only statistically significant correlations are shown.

Results

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

The dominant cyanobacteria were a range of coccoid, colony-forming genera (\textit{Aphanocapsa, Aphanothece, Cyanodictyon, Microcystis, Synechococcus} and \textit{Merismopedia}) as well as the solitary filamentous genera (\textit{Cylindrospermopsis, Planktolyngbya} and \textit{Pseudanabaena}) (Table 2). \textit{Aphanocapsa} was numerically the most common across the reservoirs and Somerset reservoir had the highest cell concentrations. Potentially toxic cyanobacteria were occasionally present in all reservoirs, with \textit{Cylindrospermopsis raciborskii} being the most prevalent in North Pine, Somerset and Wivenhoe reservoirs, and \textit{Microcystis aeruginosa} in Leslie Harrison (Table 3). \textit{Anabaena circinalis} and \textit{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 substantially 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
either total cyanobacterial cell concentrations or cell concentrations of genera capable of producing geosmin and/or MIB.

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

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

An MDS plot of algal species composition was also compared across reservoirs: Hinze and Little Nerang grouped, while North Pine, Somerset and Wivenhoe also grouped (Fig. 7). Leslie Harrison was distinctly different from all other reservoirs. MDS plots of algal species composition over time showed that October 2004, which was pre-rainfall and early in the summer, was significantly different ($P < 0.05$) from the other sampling occasions (Fig. 8).
The multivariate water quality parameters (TN, TP, turbidity, Secchi depth, bottom oxygen, chlorophyll *a*) were significantly correlated ($P<0.01$) with percentage agriculture, forest in the watershed and rainfall, but not with reservoir volume or watershed area, or (watershed area * residence time)/ reservoir volume. Algal species composition was significantly correlated ($P<0.01$) with rainfall, reservoir volume, watershed size, percentage agriculture, and forest in the watershed, but not watershed area or (watershed area * residence time)/ reservoir volume.

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

**Discussion**

This study has shown a correlation between watershed land use and algal cell, TN and TP concentrations in seven subtropical reservoirs. This is presumably due to the increased nutrient loads from anthropogenically modified watersheds entering the reservoirs and is consistent with findings in temperate reservoirs and lakes. A study of thirty lake watersheds in Connecticut, USA, also found that the proportion forest cover, urban and agricultural land were significantly correlated with TN and TP in the
corresponding lakes (Field et al., 1996).

Similarly, a study of twelve reservoirs in Ohio, USA, found that watershed land use correlated with primary production, TP and chlorophyll but there was a well defined upper limit to the effect of land use on these three parameters (Knoll et al., 2003). However, the correlation was greatly improved when land use was combined with the ratio of watershed land area to reservoir volume, and the ratio of cropland area to number of livestock. Our study also found that the ratio of watershed area * residence time/reservoir volume was significantly correlated with algal cell concentrations. This is not surprising as a larger watershed area is likely to contribute more nutrients per volume of reservoir, than a smaller watershed.

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

Short term studies of watershed effects on water quality may mask the long term effects of climate. Paleolimnological studies provide a means to differentiate climate versus land use effects. A paleolimnological study in a Canadian lake found that land use parameters (rural and urban) were stronger determinants of increased algal
biomass, and nuisance cyanobacterial species, than climatic factors (Hall et al., 1999).

In addition, paleolimnological studies in Florida lakes have also shown that cyanobacterial proliferation increased recently and abruptly in response to eutrophication (Riedinger-Whitmore et al., 2005).

In addition to the increases in the total nutrient loads with watershed modification, the quality of the nutrients may also change. Forested watersheds typically export more dissolved organic nitrogen than altered watersheds (Harris 2001). Since DON is generally less bioavailable, it is less likely to contribute directly to algal growth. The nitrogen:phosphorus ratio may also be affected. A study of 113 lakes in Iowa, USA, found that lakes in watershed with large areas of pasturelands had low nitrogen:phosphorus ratios, which are usually associated with cyanobacterial blooms (Arbuckle and Downing 2001). However in our study, the nitrogen:phosphorus ratios in all reservoirs were higher than Redfield (1958) ratios suggesting that nitrogen was present in excess, relative to phosphorus, despite the dominance of cyanobacteria. Australian reservoirs typically act as phosphorus sinks when retention times are more than one year (Harris 2001), which is the case in the subtropical reservoirs in this study. A study of one of these reservoirs, North Pine reservoir, found that cyanobacteria capable of fixing nitrogen dominated despite the high dissolved inorganic nitrogen concentrations, and indeed were very effective at utilizing these sources (Burford et al., 2006). Phosphorus is more likely to be bound to particles in the sediment than nitrogen.

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

In contrast, the relatively low TP and phosphate concentrations in the reservoirs in this study suggest that either the rate of sediment remineralization of phosphorus was low compared with nitrogen, or alternatively that phosphorus loads entering the reservoir were low. Further work is needed to determine the relative importance of these processes. However, reservoir depth in two Portuguese reservoirs was found to be a better determinant of trophic status than nutrient loading from the watershed (Matias and Boavida 2005). Similarly, in a study of 86 lakes in Ontario, Canada, TN 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.
Watershed area and the ratio of watershed area * residence time/reservoir volume were significantly correlated with algal cell concentrations, suggesting that reservoir characteristics cannot be ignored.

Acknowledgements

We wish to thank the following: the boat drivers at SEQWater, Gold Coast Water, Brisbane Water and Redland Water and Waste who assisted with sampling, Dan Wruck and his team for nutrient analyses, Karen Reardon for algal identification and enumeration, Bob Gray and this team for analysis of taste/odour compounds, Jason Kerr for data entry, Tony McAlister for data on watershed land use, and Mark O’Donohue for useful discussions. The work was supported by a Griffith University Industry Collaborative Scheme, SEQWater Corporation, Gold Coast Water, Redland Water and Waste, and Brisbane Water.
References


Harris, G. (2001) Biogeochemistry of nitrogen and phosphorus in Australian watersheds, rivers and estuaries: effects of land use and flow regulation and comparisons with global patterns. Marine and Freshwater Research 52 (1), 139-149.


Figure Legend

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

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

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

Figure 4: Mean dissolved nutrient concentrations (+ SD, mg L$^{-1}$, n=3) on the surface and bottom in the seven reservoirs. Only measured in February 2006. nd = < 0.002 mg L$^{-1}$

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

Figure 6: MDS of the water quality parameters (TN, TP, turbidity, Secchi depth, oxygen, chlorophyll a concentrations) in the seven reservoirs across the four sampling occasions.
Figure 7: MDS of algal species composition in the seven reservoirs across the four sampling occasions.

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

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

<table>
<thead>
<tr>
<th>Genera</th>
<th>Hinze</th>
<th>Leslie</th>
<th>Little</th>
<th>Manchester</th>
<th>North Pine</th>
<th>Somerset</th>
<th>Wivenhoe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Harrison</td>
<td>Nerang</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Planktolyngbya</strong></td>
<td>149,000 (148,000)</td>
<td>34,000 (41,000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cyanodictyon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aphanocapsa</td>
<td>14,000 (7,000)</td>
<td>91,000 (140,000)</td>
<td>21,000 (31,000)</td>
<td>13,000 (8,000)</td>
<td>47,000 (35,000)</td>
<td>72,000 (53,000)</td>
<td>59,000 (59,000)</td>
</tr>
<tr>
<td>Synechococcus</td>
<td></td>
<td>40,000 (35,000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cylindrospermopsis raciborskii</strong></td>
<td>30,000 (30,000)</td>
<td>14,000 (16,000)</td>
<td>10,000 (19,000)</td>
<td>14,000 (19,000)</td>
<td>26,000 (31,000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Aphanothece</strong></td>
<td></td>
<td></td>
<td>15,000 (14,000)</td>
<td>13,000 (15,000)</td>
<td>14,000 (10,000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Microcystis aeruginosa</strong></td>
<td>14,000 (16,000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total cell concentrations</strong></td>
<td>66,000 (17,000)</td>
<td>54,000 (41,000)</td>
<td>227,000 (238,000)</td>
<td>101,000 (30,000)</td>
<td>328,000 (32,000)</td>
<td>565,000 (229,000)</td>
<td>360,000 (155,000)</td>
</tr>
</tbody>
</table>
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$^{-1}$.

<table>
<thead>
<tr>
<th>Species</th>
<th>Date</th>
<th>Hinze</th>
<th>Leslie Harrison</th>
<th>Little Nerang</th>
<th>Manchester</th>
<th>North Pine</th>
<th>Somerset</th>
<th>Wivenhoe</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Microcystis aeruginosa</em></td>
<td>Oct’04</td>
<td>40</td>
<td></td>
<td></td>
<td>1,330</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dec’04</td>
<td>3,010</td>
<td>35,880</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feb’05</td>
<td>10</td>
<td>5,940</td>
<td>3,250</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Apr’05</td>
<td>100</td>
<td>7,000</td>
<td>6,380</td>
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<tr>
<td><em>Cylindrospermopsis raciborskii</em></td>
<td>Oct’04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>340</td>
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<tr>
<td></td>
<td>Dec’04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17,770</td>
<td>6,590</td>
<td>2,630</td>
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<td>Feb’05</td>
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<td></td>
<td>1,500</td>
<td>63,390</td>
<td>22,330</td>
<td>18,380</td>
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<tr>
<td></td>
<td>Apr’05</td>
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<td></td>
<td>9,570</td>
<td>38,090</td>
<td>1,300</td>
<td>2,300</td>
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<tr>
<td><em>Anabaena circinalis</em></td>
<td>Oct’04</td>
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<td></td>
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<tr>
<td></td>
<td>Dec’04</td>
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<td>140</td>
<td>710</td>
<td>200</td>
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<td>Feb’05</td>
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<td>Apr’05</td>
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<td>110</td>
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<tr>
<td><em>Aphanizomenon ovalisporum</em></td>
<td>Oct’04</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Dec’04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feb’05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>320</td>
<td>1,530</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Apr’05</td>
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</tr>
</tbody>
</table>
Table 4: Mean (± SD) of TN, TP (mg L\textsuperscript{-1}), TN:TP molar ratios and chlorophyll \(a\) (µg L\textsuperscript{-1}) across surface and bottom waters, sampling occasions, and within-reservoir sites for the seven reservoirs in the study.

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

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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Correlated with</th>
<th>N</th>
<th>Rho</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total algal cell concentrations</td>
<td>% Forest</td>
<td>56</td>
<td>-0.421</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td></td>
<td>Watershed area</td>
<td></td>
<td>0.527</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Reservoir volume</td>
<td></td>
<td>0.405</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td></td>
<td>Watershed area*residence time/reservoir volume+</td>
<td>48</td>
<td>0.430</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Chlorophyll ( a )</td>
<td>Rainfall</td>
<td>56</td>
<td>0.371</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TN</td>
<td>% Forest</td>
<td>56</td>
<td>-0.550</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>%Agriculture</td>
<td></td>
<td>0.500</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Watershed area</td>
<td></td>
<td>0.364</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td></td>
<td>-0.715</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TP</td>
<td>% Forest</td>
<td>56</td>
<td>-0.383</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td></td>
<td>% Agriculture</td>
<td></td>
<td>0.286</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>
Fig. 2

Increasing watershed area

- Little Nerang
- Manchester
- Leslie Harrison
- Hinze
- North Pine
- Somerset
- Wivenhoe

% land use

- % residential
- % agriculture
- % forest
Figure 3

Cell densities mL$^{-1}$

October 2004

December 2004

February 2005

April 2005

Others

Cyanobacteria

Cell densities mL$^{-1}$
Fig. 4

Phosphate

Oxides of nitrogen

Ammonium
Fig. 5

Rainfall (mm)

% change in water level

Aug-Oct'04  Oct-Dec'04  Dec-Feb'05  Feb-Apr'05
Fig. 6
Fig. 7
Fig 8