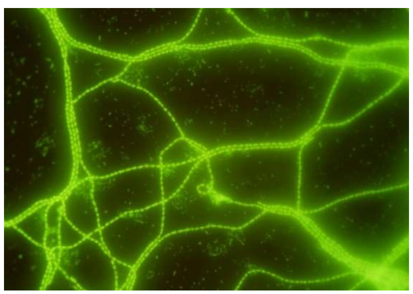
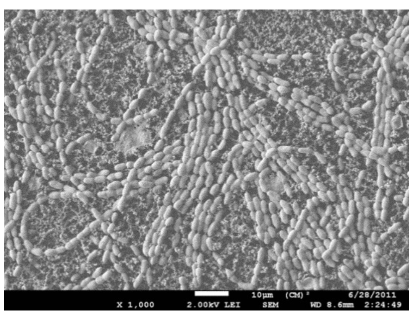
INVESTIGATING WATER TREATMENT PROCESSES FOR REMOVAL OF TASTE AND ODOUR COMPOUNDS: FOCUS ALGAE



@ArashZamyadi

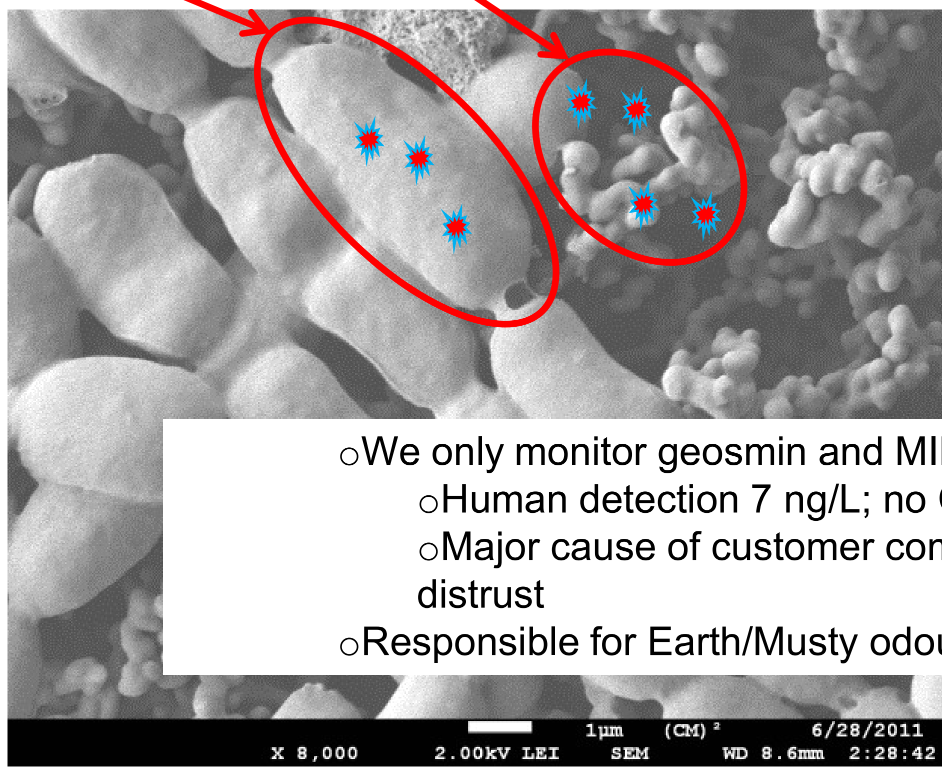
International Water Association (IWA) Fellow





Cell Identification/Integrity & Release

Intra- and extracellular compounds



- We only monitor geosmin and MIB
  - Human detection 7 ng/L; no Cl2
  - Major cause of customer complaints & distrust
- Responsible for Earth/Musty odour

ALGAL BLOOM AND T&O MONITORING PATHWAYS

Sample Multiple Locations in waterbody

Chlorophyll and Phycocyanin probes help justify when a trip to the field is required.

FlowCam Cyano: identify organisms, plus count, and concentration.

Toxin Path

qPCR

Dip Sticks

Thermo LC-MS/MS

T&O Path

Thermo GC-MS/ECD to quantify MIB/Geosmin

Monitoring of Benthic Cyanobacteria

Benthic cyanobacteria can be a significant source of cyanotoxins and T&O compounds[3]. However, only 20% of utility respondents include benthic monitoring in their routine sampling. Benthic cyanobacteria may explain instances where metabolites are detected in a water supply without visible evidence of a bloom. Figure 8 illustrates benthic cyanobacteria in surface water sources and corresponding sampling methods. Figure 9 presents a decision tree to evaluate potential risks related to benthic cyanobacteria.

Figure 8. Summary of benthic cyanobacteria sources and available sampling methods.

3 Gaget, V., Almuhtaram, H., Kibuye, F. A., Hobson, P., Zamyadi, A., Brookes, J. D., Trends in production of benthic secondary metabolites across different climates-In preparation

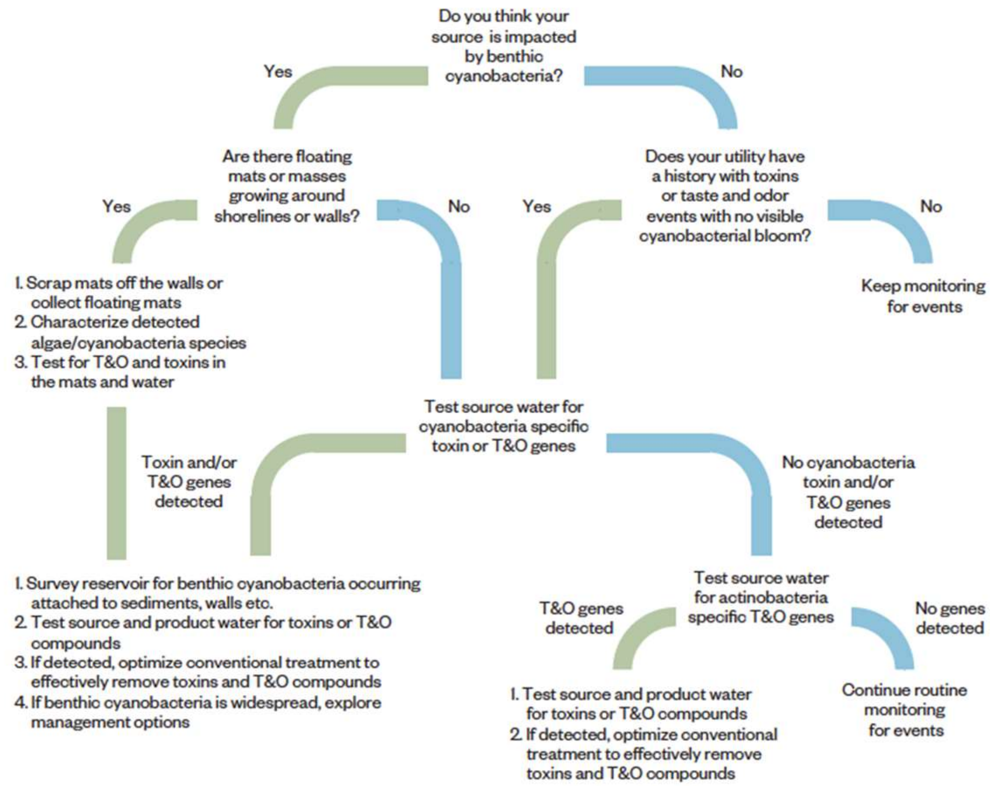
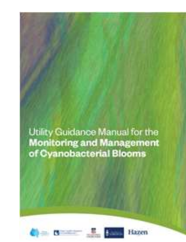
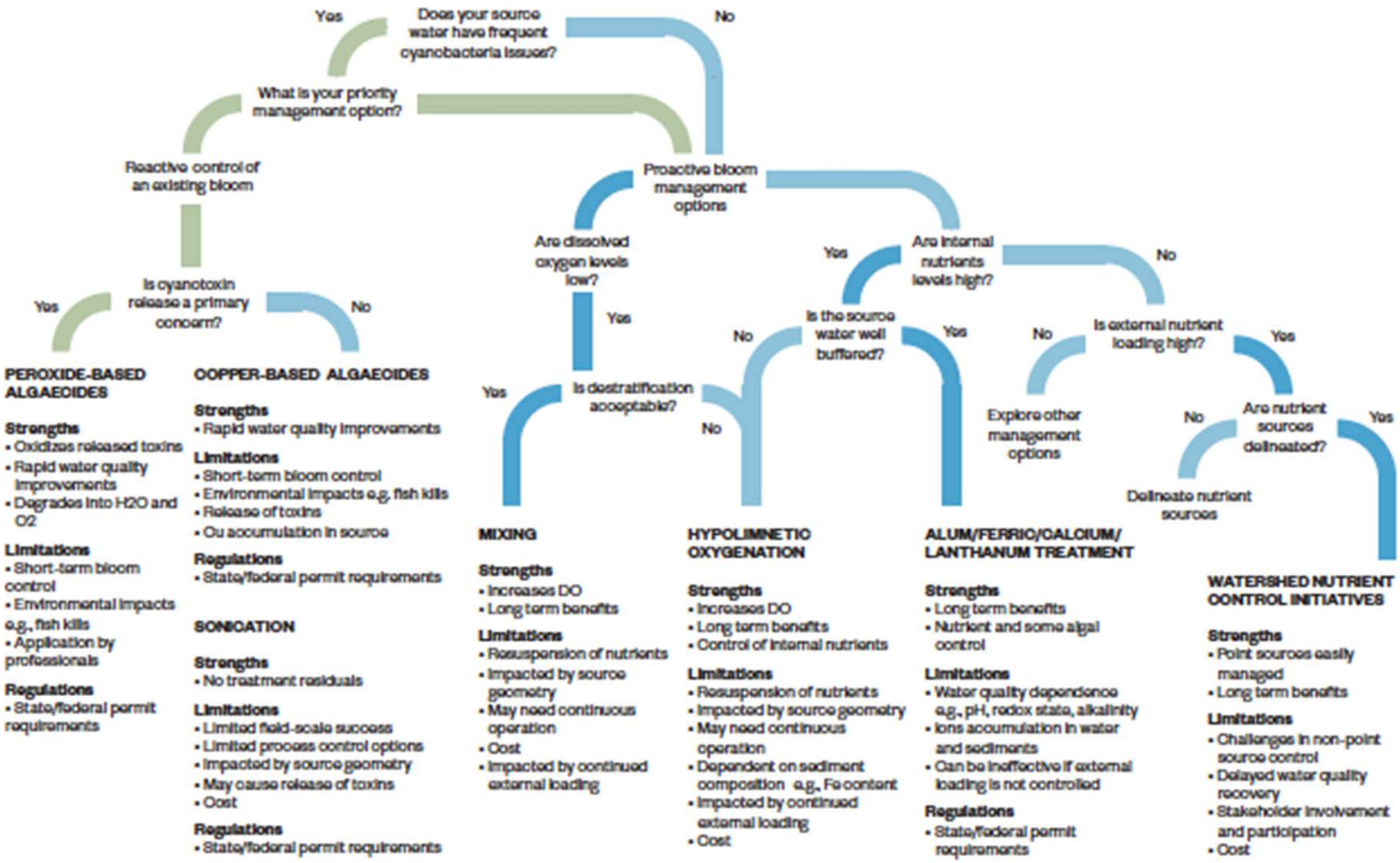


Figure 9. Decision tree on determining issues with benthic cyanobacteria at the drinking water source

Gaget et. al (2021) “Benthic cyanobacteria: a utility-centered field study”; Under review




Does your source water have frequent cyanobacteria issues?
Yes
No
What is your priority management option?
Reactive control of an existing bloom
Proactive bloom management options
Is cyanotoxin release a primary concern?
Yes
No
PEROXIDE-BASED ALGAECIDES
Strengths
• Oxidizes released toxins
• Rapid water quality improvements
• Degrades into H2O and O2
Limitations
• Short-term bloom control
• Environmental impacts e.g., fish kills
• Application by professionals
Regulations
• State/federal permit requirements
COPPER-BASED ALGAECIDES
Strengths
• Rapid water quality improvements
Limitations
• Short-term bloom control
• Environmental impacts e.g. fish kills
• Release of toxins
• Cu accumulation in source
Regulations
• State/federal permit requirements
SONICATION
Strengths
• No treatment residuals
Limitations
• Limited field-scale success
• Limited process control options
• Impacted by source geometry
• May cause release of toxins
• Cost
Regulations
• State/federal permit requirements
Are dissolved oxygen levels low?
Yes
Is destratification acceptable?
Yes
No
MIXING
Strengths
• Increases DO
• Long term benefits
Limitations
• Resuspension of nutrients
• Impacted by source geometry
• May need continuous operation
• Cost
• Impacted by continued external loading
HYPOLIMNETIC OXYGENATION
Strengths
• Increases DO
• Long term benefits
• Control of internal nutrients
Limitations
• Resuspension of nutrients
• Impacted by source geometry
• May need continuous operation
• Dependent on sediment composition e.g., Fe content
• Impacted by continued external loading
• Cost
Are internal nutrients levels high?
Yes
No
Is the source water well buffered?
No
Yes
ALUM/FERRIC/CALCIUM/ LANTHANUM TREATMENT
Strengths
• Long term benefits
• Nutrient and some algal control
Limitations
• Water quality dependence e.g., pH, redox state, alkalinity
• Ions accumulation in water and sediments
• Can be ineffective if external loading is not controlled
Regulations
• State/federal permit requirements
Is external nutrient loading high?
No
Yes
Explore other management options
Are nutrient sources delineated?
No
Yes
Delineate nutrient sources
WATERSHED NUTRIENT CONTROL INITIATIVES
Strengths
• Point sources easily managed
• Long term benefits
Limitations
• Challenges in non-point source control
• Delayed water quality recovery
• Stakeholder involvement and participation
• Cost

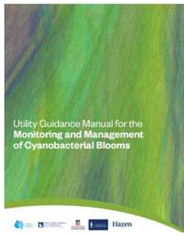
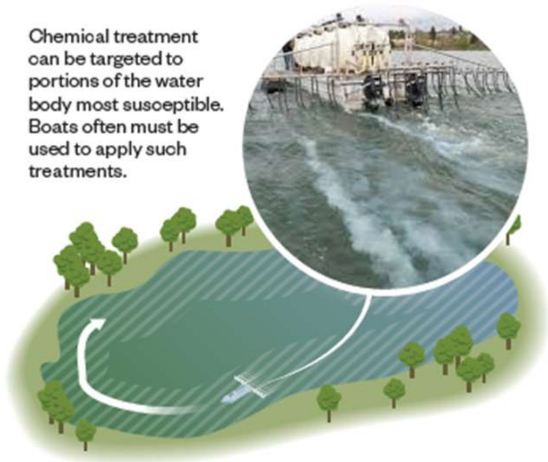

Utility Guidance Manual for the Monitoring and Management of Cyanobacterial Blooms

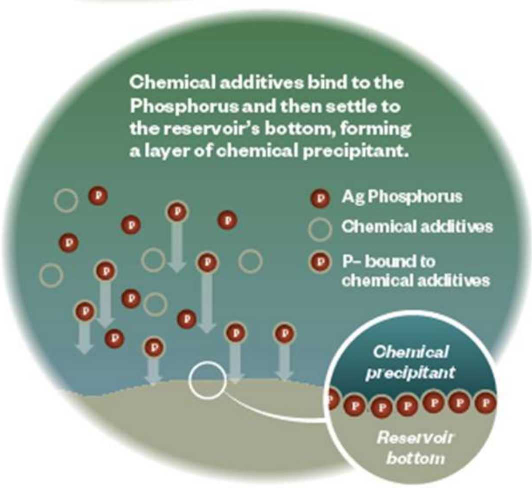
Table 2: Summary table of source water control strategies

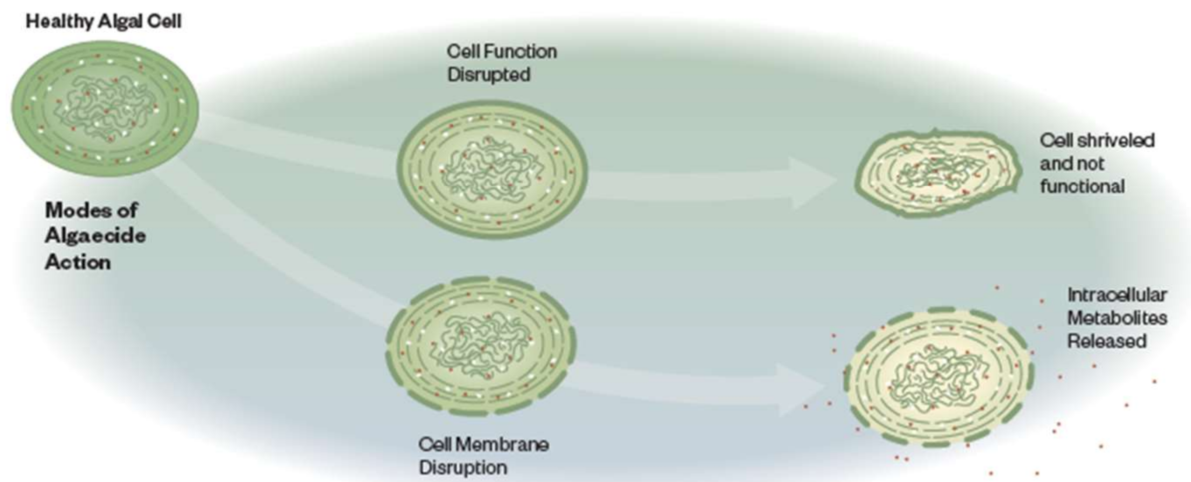
Primary Considerations	ALGAECIDES		NUTRIENT SEQUESTRATION				Aeration	Sonication	Biological Control
	Hydrogen Peroxide	Copper sulfate	Polyaluminium Chloride	Aluminium Sulfate	Iron	Modified Clay			
Application									
Pelagic Zone (i.e. water column)	Applicable	Applicable	Applicable	Applicable		Applicable	Applicable	Applicable	Applicable
Benthic Zone (i.e. sediment surface)	Dependent on treatment method and type of chemical used	Dependent on treatment method and type of chemical used	Applicable	Applicable	Applicable	Not applicable	Not applicable	Applicable	Applicable
Benefits									
Proactive Strategy	Not applicable	Not applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Not applicable	Applicable
Reactive Strategy	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable
Nutrient Removal	Not applicable	Not applicable	Applicable	Applicable	Applicable	Applicable	Lowers release of reduced ions	Not applicable	Applicable for macrophytes
Duration of Treatment Effect	7-30 days	14-60 days	4-20 yrs	4-20 yrs	1 yr	2-9 yrs	Continous: based on operational characteristics	Continous: based on operational characteristics	Continous: based on operational characteristics
Short-Term Response	80-99% reduction of cyanobacteria	>90% reduction of cyanobacteria	97% reduction in total P	30% reduction in internal P loading	Increased transparency; up to72% decline in chlorophyll-a;	<65% reduction in total P	Increased DO levels at 1 mg/L/wk and reduced internal nutrient loading	30-90% reduction in cell counts	Increased water transparency; decreased chlorophyll-a and P
Long-Term Response	≥75% for up to 60 days	≥75% for up to 60 days	80-95% reduction in internal P loading	50-80% reduction in internal P loading	50-80% reduction in internal P loading	Upto 80% reduction in total P	Maintaining high DO levels for up to 23 yrs	Limited field-application success	Improvement in water quality conditions
Limitations									
Treatment Residuals	None	Cu^{2+} residual in water column and sediments	Al^{3+} residual in sediments	Al^{3+} residual in sediments	Fe^{3+}residual in water column and sediment	Release of trace metals, La^{3+} & NH_4^+ in water columns	None	None	None
Cell Lysis/Metabolite Release	Dose-dependent release. Oxidizes released toxins	Dose Dependent	None	None		None	None	Can release toxins depnding on operational characteristics	None
Background Interferences	None	pH sensitivity; sensitivity of cyanobacteria species to Cu; timing of treatment relative to growth stage	pH sensitivity; source water morphology and geometry; source mixing characteristics; continued external nutrient inputs	pH sensitivity; source water morphology and geometry; source mixing characteristics; continued external nutrient inputs	Redox sensitivity; continued external nutrient inputs;	pH sensitivity; source water morphology and geometry; source mixing characteristics; continued external nutrient inputs	Source water morphology and geometry; continued external nutrient inputs; sediment composition e.g. iron content of the sediment water interphase	Source water morphology and geometry	Water quality conditions; % macrophyte cover; continued external nutrient inputs; time for community establishment at the source
Environmental Impacts	Occassional fish kills depending on treatment dosage	Occassional fish kills depending on treatment dosage	Minimal impacts on aquatic organisms	Minimal impacts on aquatic organisms	High levels of Fe can negatively impacts aquatic organisms	Minimal impacts on aquatic organisms	May alter aquatic habitats due to impacts on hypolimnetic temperature;	Minimal impacts on aquatic organisms	None
Acceptance Level									
Field Application History	5-15 years	>15 years	5-15 years	>15 years	>15 years	5-15 years	>15 years	5-15 years	5-15 years
Peer Reviewed Literature	3-10 papers	>10 Papers	3-10 papers	3-10 papers	3-10 papers	3-10 papers	>10 Papers	3-10 papers	3-10 papers
Ease of Implementation									
Permit Required (i.e. State Dependent)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Expertise and Training	Professionally applied	Professionally applied					No	No	No
Process Control (i.e. Dose, Residuals)	mg/L H_2O_2	mg/L Cu or $CuSO_4$	mg/L Al or $Al_2Cl(OH)_5$	mg/L Al or $Al_2(SO_4)_3$	kg/ha	kg/ha	Mixing rate/ intensity	Sonication frequency (kHz); May rely on manufacturer to remotley adjust operational parameters	#of fish removed/ added; % macrophyte cover; g of straw/ m^3

CHEMICAL CONTROL STRATEGIES



Chemical treatment methods consist of algaecides and nutrient sequestering chemicals frequently are applied by boat. Copper and peroxide-based algaecides damage cellular integrity and cause cell death (Figure 11), limiting bloom expansion in a drinking water source. Nutrient sequestering additives such as alum, polyaluminum chloride (PACl), iron salts, and bentonite clays bind P in the water column, creating nutrient limited conditions that inhibit cyanobacteria growth. A detailed review of chemical methods is available[4].





K.E. Greenstein, A. Zamyadi, C.M. Glover, C. Adams, E. Rosenfeldt, E.C. Wert (2020) Delayed Release of Intracellular Microcystin Following Partial Oxidation of Cultured and Naturally Occurring Cyanobacteria. Toxins, 12(5), 335.

A. Zamyadi, K. E. Greenstein, C. M. Glover, C. Adams, E. Rosenfeldt, E. C. Wert (2020) Impact of hydrogen peroxide and copper sulfate on the delayed release of microcystin. Water, 12(4).

Kibuye et. al (2021) "A critical review on operation and performance of source water control strategies for cyanobacterial blooms: Part I-chemical control methods"

Figure 13. Summary of biological control methods and factors to consider for implementation.

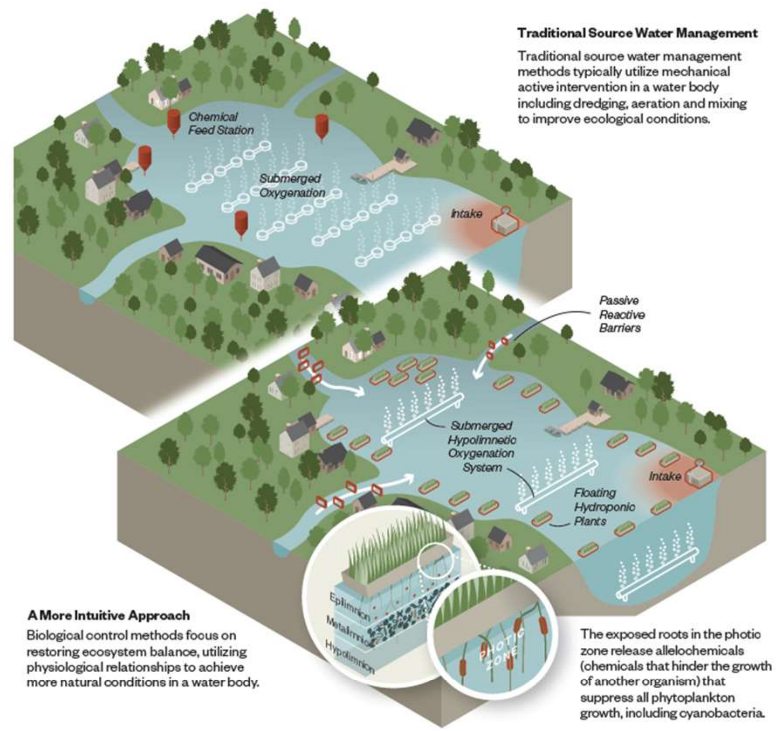


Figure 12. Summary of mechanical control methods and factors to consider/influencing treatment efficacy

Kibuye et. al (2021) “A critical review on operation and performance of source water control strategies for cyanobacterial blooms: Part II-mechanical and biological control methods”; ACCEPTED!

Protocols for algal bloom management

Source mitigation using sonication

Trial package for Intelligent Water Network (IWN) & Veolia:

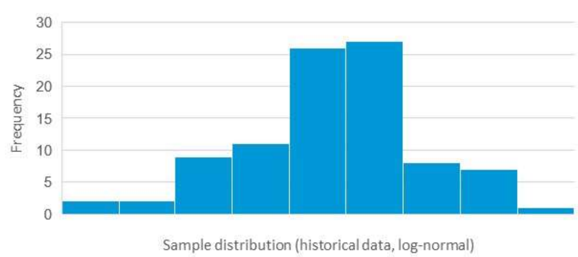
- **Trialling of non-chemical dosing for cyanobacteria mitigation at the source**
- **Developed the sampling protocol to collect systematic algal and cyanobacterial, and water quality data**
- **Sonication equipment was installed Dec 2020**
- **Data analyse and interpretation is ongoing**

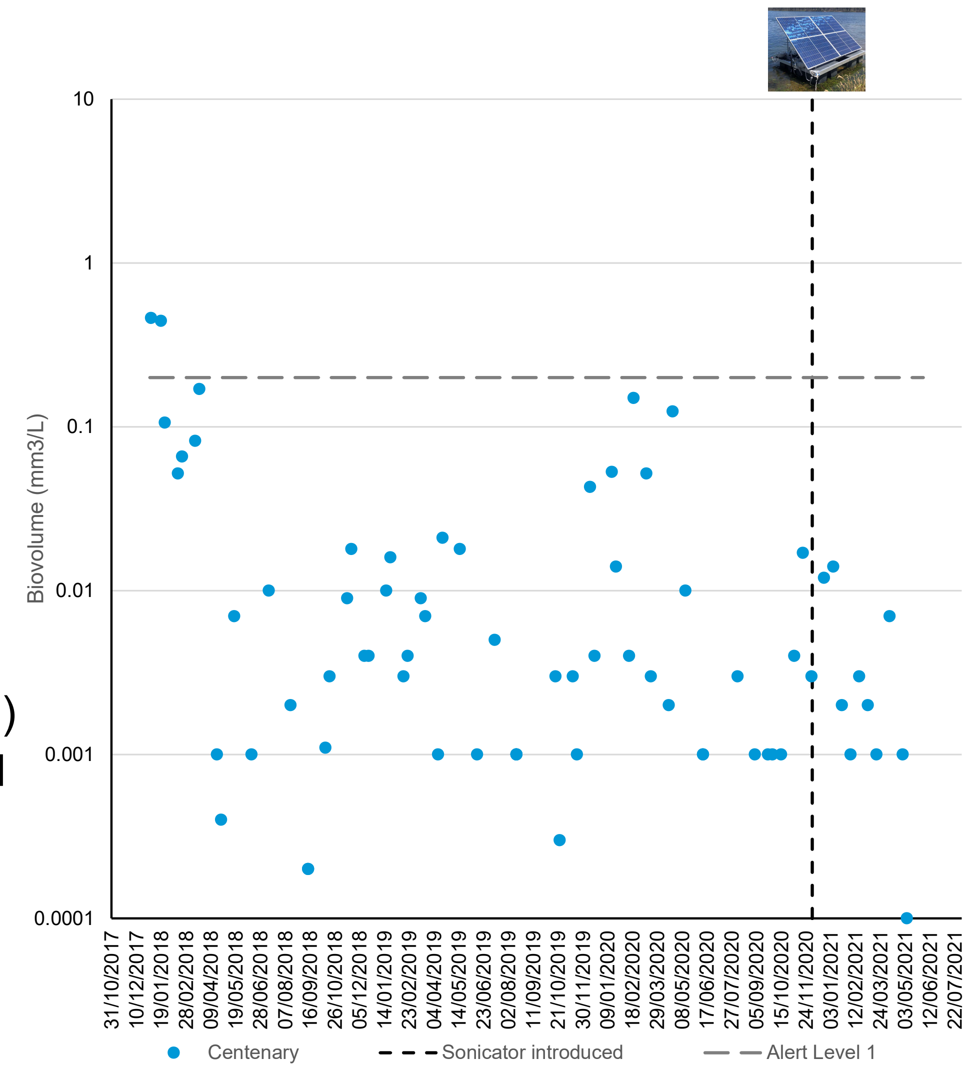
Protocols for algal bloom management

Source mitigation using sonication

Total Cyanobacteria Biovolumes – Statistical Observations

- **Preliminary analysis (Log-normal distribution)**
  - **Practicality of controls?**
  - **Data from only 1 bloom season**
  - **Testing is lower during non-bloom periods**
- Centenary Reservoir Walkway
  - Historical distribution (n=56) compared to post-sonicator distribution (n=10)
  - Statistically significant difference observed
- Water treatment plant intake stream
  - Historical (n=94) and post-sonicator (n=20)
  - Statistically significant difference observed



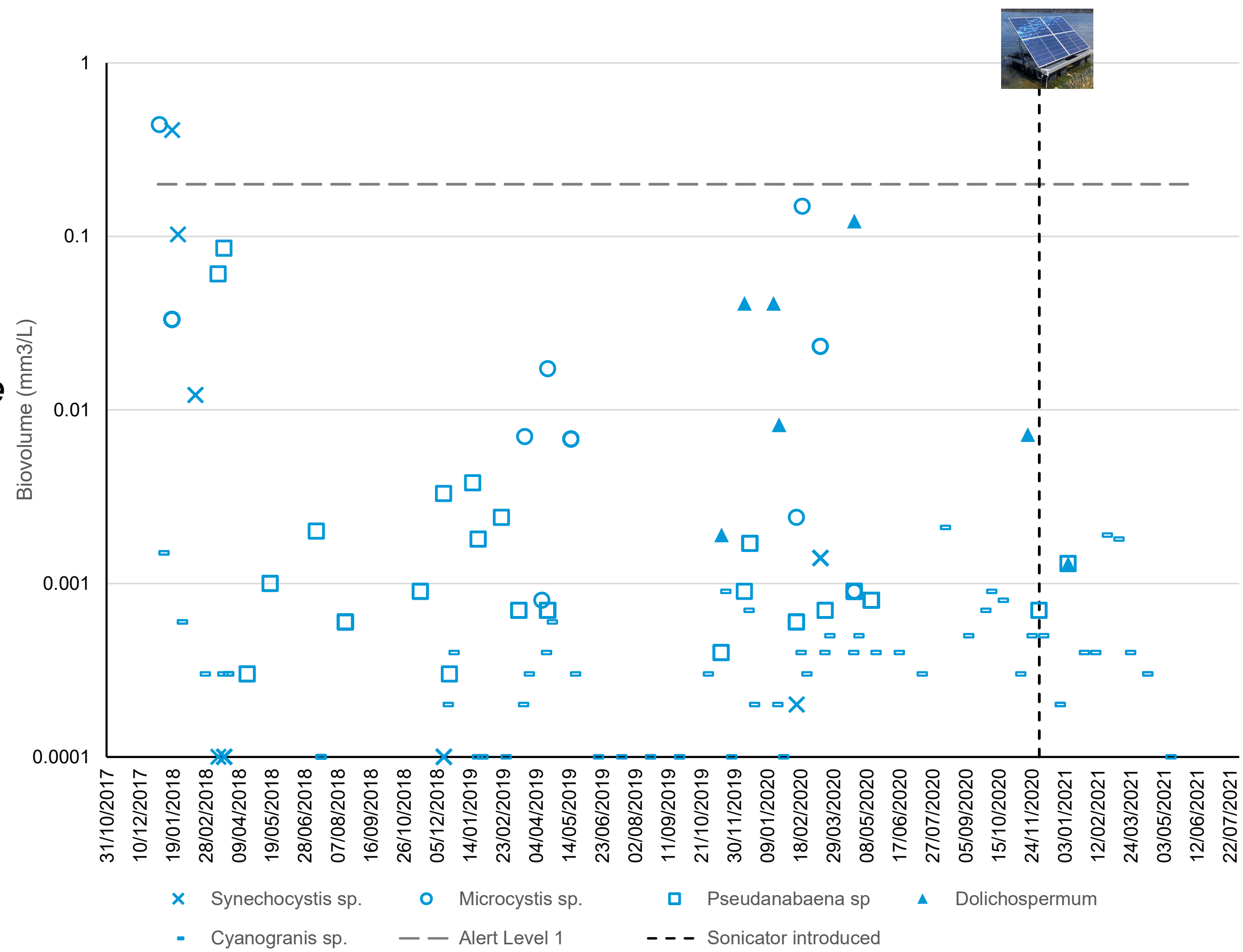


Protocols for algal bloom management

Source mitigation using sonication

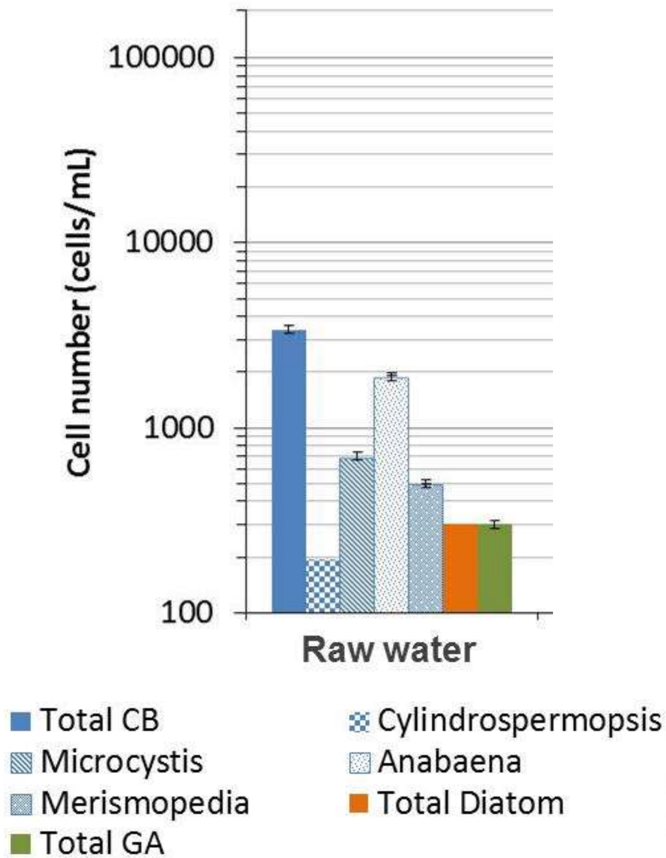
Dominant Cyanobacteria Species Biovolumes – Centenary Reservoir

- Disruptions in dominant species observed after sonicator installation
- *Microcystis sp.* undetected in 2020/2021 bloom season
- *Cyanogranis sp.* and *Anathece sp.* dominant in recent blooms

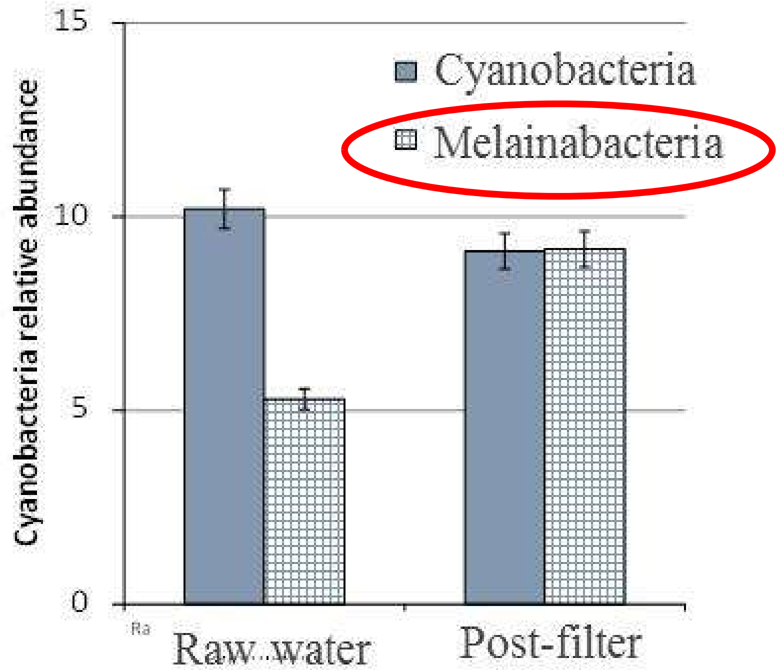


TREATMENT ISSUES/UNKNOWNS?

Identified organisms using macroscopic taxonomy



Extra info obtained by genomics



Water Research 152 (2019) 96–105

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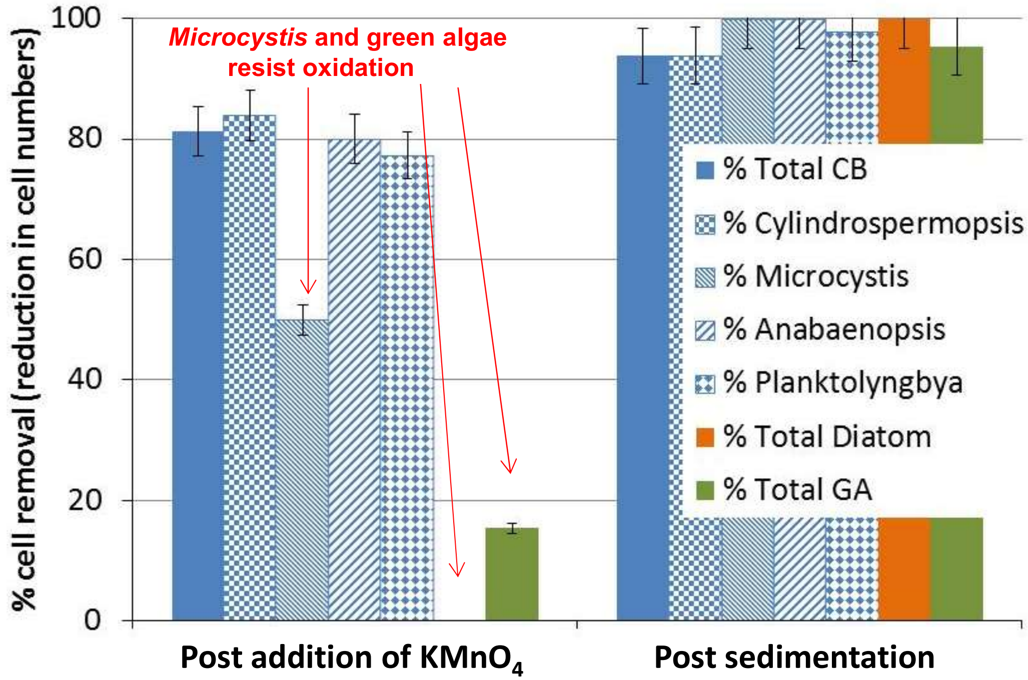
Diagnosing water treatment critical control points for cyanobacterial removal: Exploring benefits of combined microscopy, next-generation sequencing, and cell integrity methods

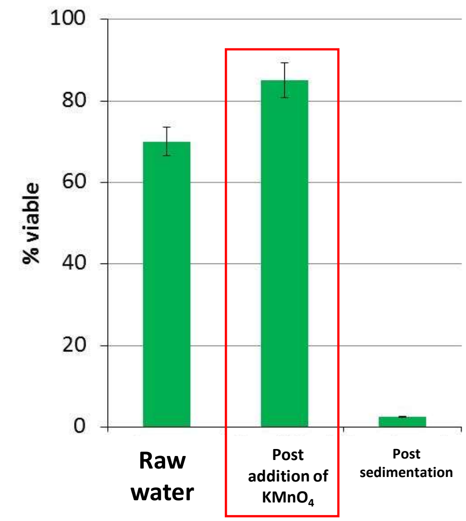
Arash Zamyadi [a, b, c, *], Caitlin Romanis [d], Toby Mills [d], Brett Neilan [d], Florence Choo [b], Lucila A. Coral [b, e], Deb Gale [f], Gayle Newcombe [g], Nick Crosbie [h], Richard Stuetz [a], Rita K. Henderson [b]

Sampling results: Pre-oxidation using pre-$KMnO_4$:

% cell removal & total MIB



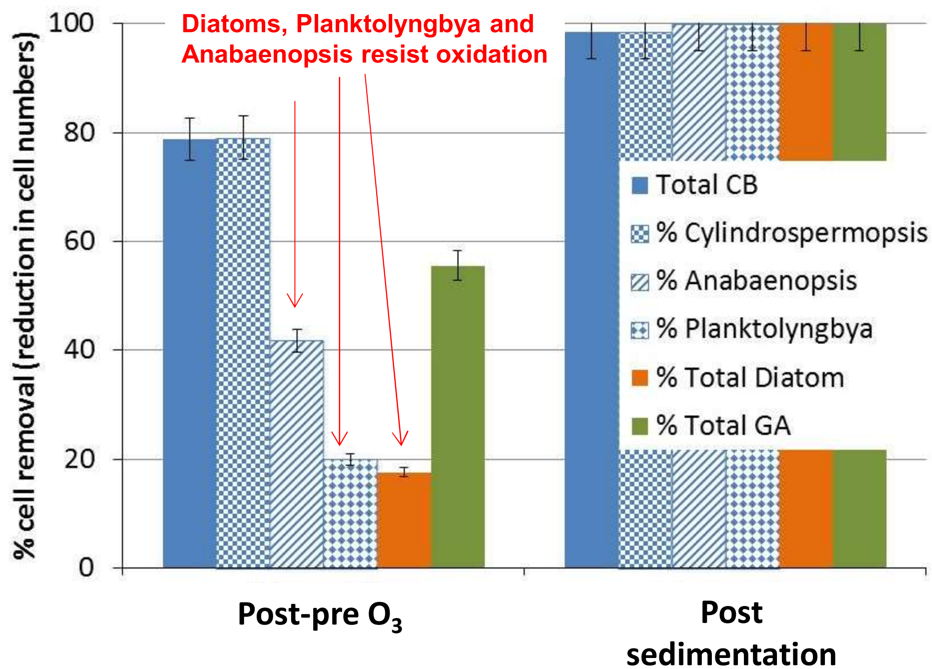
High removal rate but the remaining were healthy cells



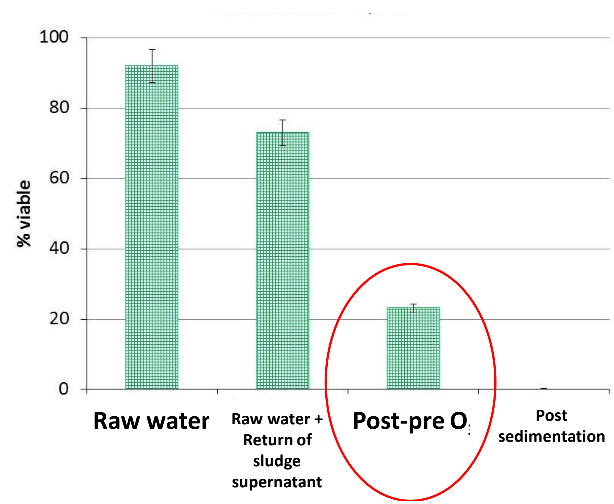
	Raw water	Raw water + KMnO4	Surface of sedimentation tank	Filtered water	Finished water
MIB (ng/L) :	**12.6**	**12.9**	**6.6**	**6.4**	**6.8**

Sampling results: Pre-oxidation using pre-O_3

% cell removal & total geosmin



High removal rate & the remaining were damaged cells



Geosmin (ng/L) :

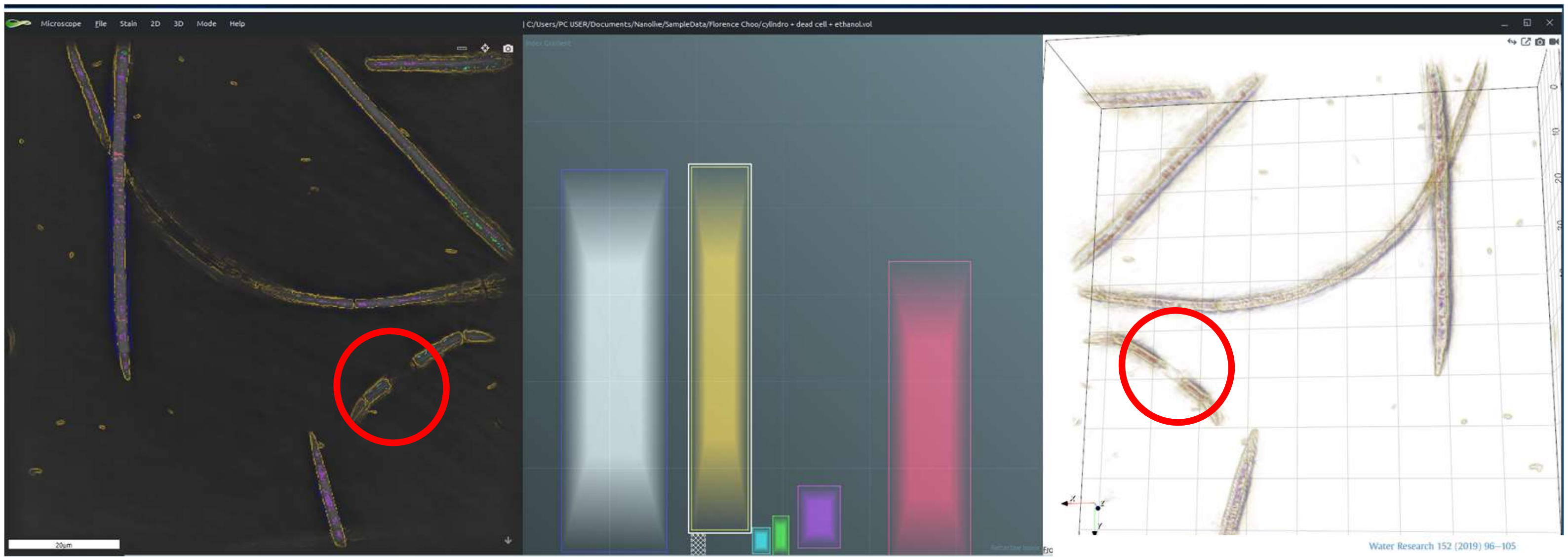
Raw water	Return of sludge recovery supernatant	Post pre-ozonation	Surface of sedimentation tank	Filtered water	Post interozonation and BAC	Finished water
15.9	15.1	8.7	7.6	BDL	BDL	BDL

Accumulation of geosmin in sludge: 20.6 ng/L

OXIDATION – UNKNOWNS?

Understand the phenomena governing cell wall damage & release of intracellular metabolites during oxidation:

Fate of Cylindrospermopsis cells post ozonation



Flowcytometry confirmed complete cells damaged but not at the same level!

Water Research 152 (2019) 96–105

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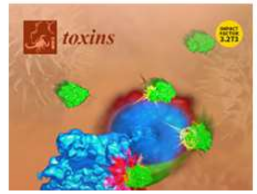
Understanding oxidation:

Understand the phenomena governing oxidation of cells, biomarker indicating toxin production, triggers of toxicity, release of intracellular metabolites

Volume 11, Issue 5

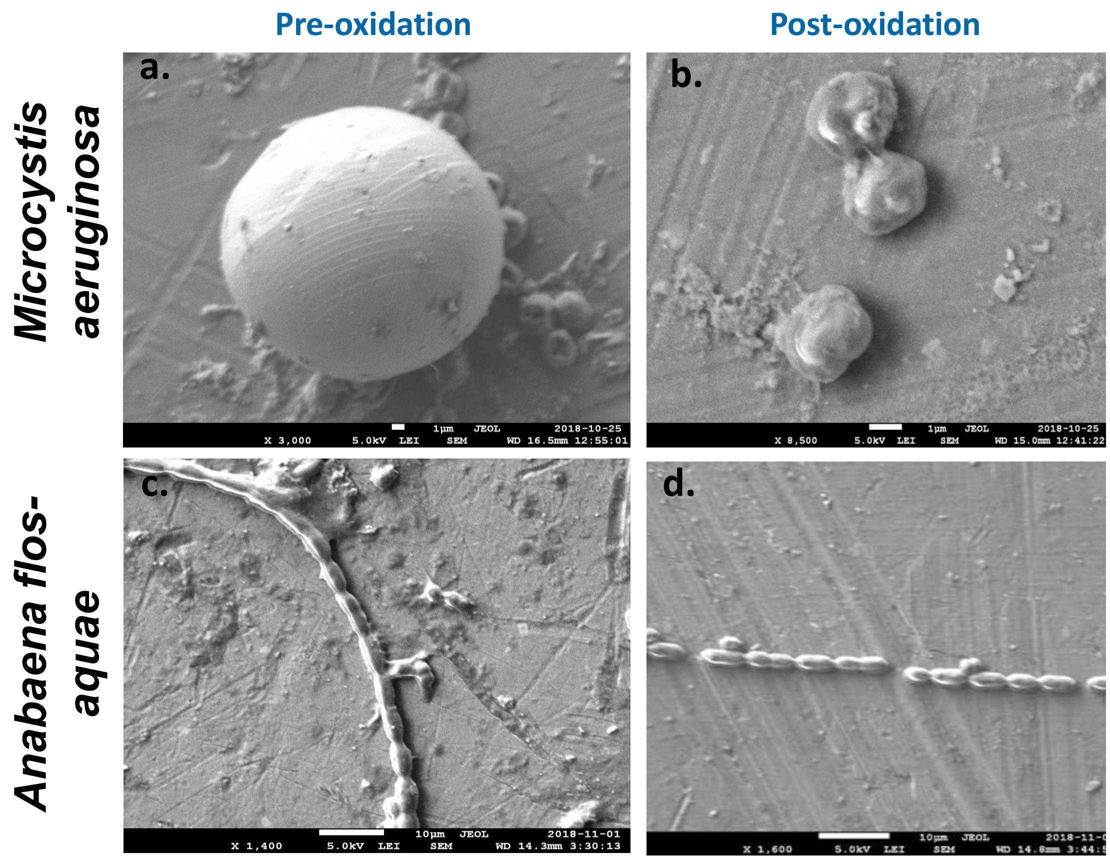


Open Access Article

Using Advanced Spectroscopy and Organic Matter Characterization to Evaluate the Impact of Oxidation on Cyanobacteria

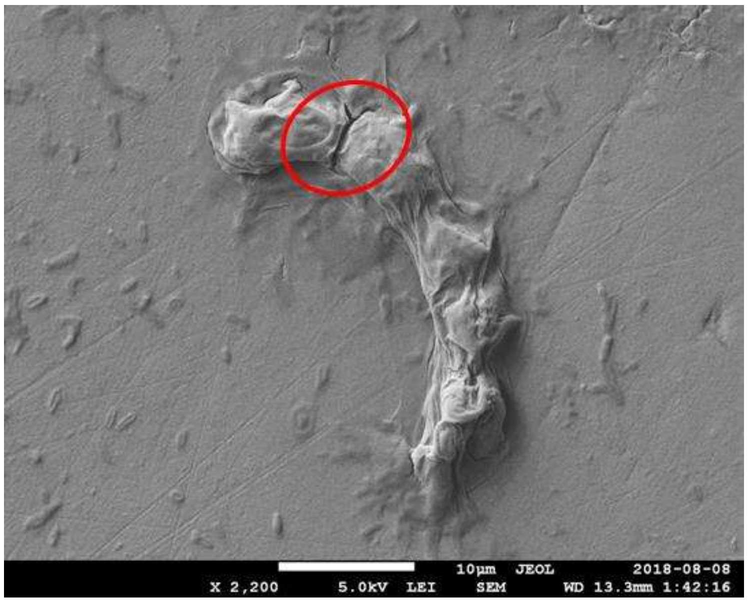
Saber Moradinejad [1], Caitlin M. Glover [1], Jacinthe Mailly [1], Tahere Zadfathollah Seighalani [1], Sigrid Peldszus [2], Benoit Barbeau [1], Sarah Dorner [1], Michèle Prévost [1] and Arash Zamyadi [1,*]

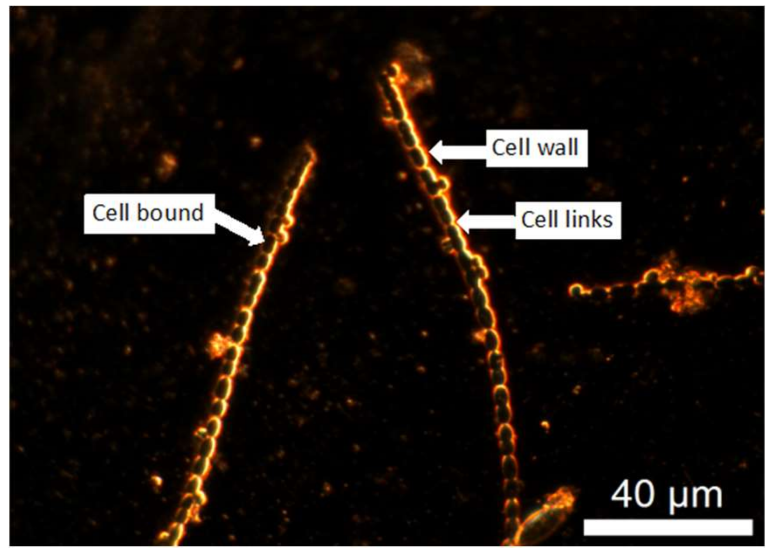
Chlorination for maximum dose-contact time (CT) 120 mg.min/L and ozonation for maximum dose-contact time (CT) 50 mg.min/L

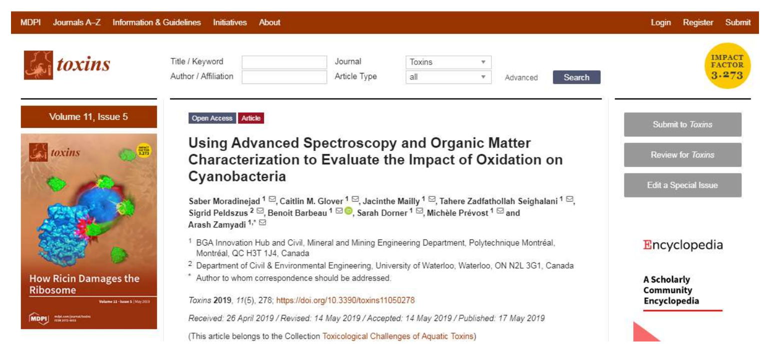


Understanding oxidation:

Enhanced Darkfield Microscopy with Hyperspectral Imaging (EDM/HSI) allows for spectra (400–1000 nm) to be generated from a specific pixel (containing a cell component of interest)



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Volume 11, Issue 5

How Ricin Damages the Ribosome

Open Access Article

Using Advanced Spectroscopy and Organic Matter Characterization to Evaluate the Impact of Oxidation on Cyanobacteria

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[1] BGA Innovation Hub and Civil, Mineral and Mining Engineering Department, Polytechnique Montréal, Montréal, QC H3T 1J4, Canada
[2] Department of Civil & Environmental Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[*] Author to whom correspondence should be addressed.

Toxins **2019**, *11*(5), 278; https://doi.org/10.3390/toxins11050278

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(This article belongs to the Collection Toxicological Challenges of Aquatic Toxins)

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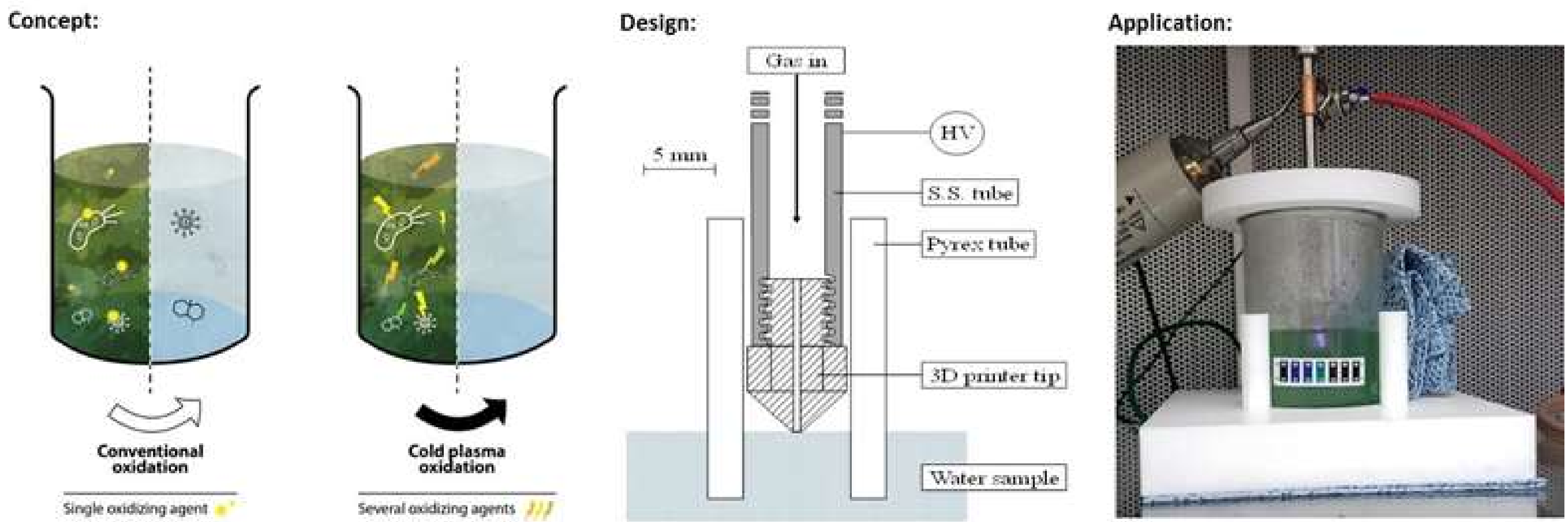
Encyclopedia
A Scholarly Community Encyclopedia

What if we oxidize them all together:



B. Nisol, S. Watson, Y. Leblanc, S. Moradinejad, M. R. Wertheimer, A. Zamyadi (2019) Cold plasma oxidation of harmful algae and associated metabolite BMAA toxin in aqueous suspension. Plasma Processes and Polymers, 16(2). https://doi.org/10.1002/ppap.201800137S

CYANOTOXIN OXIDATION

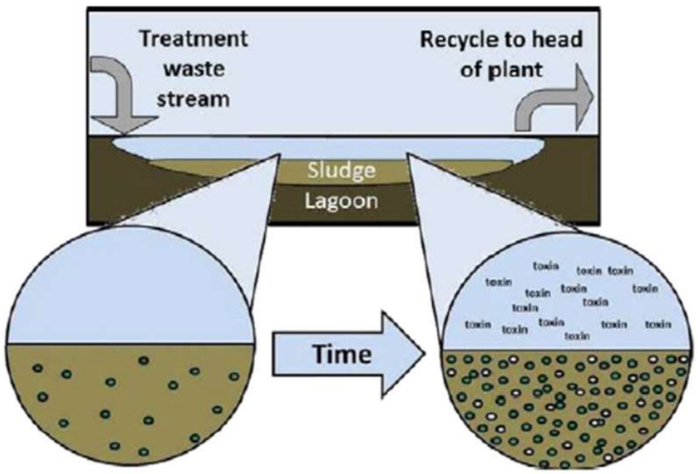
WRF4692 - #WRFCyanoToxinOxid:
Release of Intracellular Cyanotoxins During Oxidation of Naturally Occurring and Lab Cultured Cyanobacteria

Oxidant	Microcystins	Microcystin-LA	Cylindrospermopsin	Anatoxin A	Saxitoxins	GTX2, GTX3 and C1, C2	Nodularins	MIB and geosmin	BMAA
Free chlorine	pH		pH	Slow/no oxidation			pH		pH
Monochloramine	Slow/no oxidation					?			?
Chlorine dioxide	Slow/no oxidation					?	?		?
Permanganate						?	?	?	Slow
Ozone			pH	pH					pH
Hydroxyl radical					?	?			pH
UV	High doses	High doses	High doses	High doses	?	?	?	High doses	High doses
Cold plasma oxidation*	LR and LL	?	?	?	?	?	?	?	

*Treatment technology currently at bench-scale.

FATE OF CELLS?

Cell accumulation in sludge?



Source: Water Research Foundation 4315 & 4523

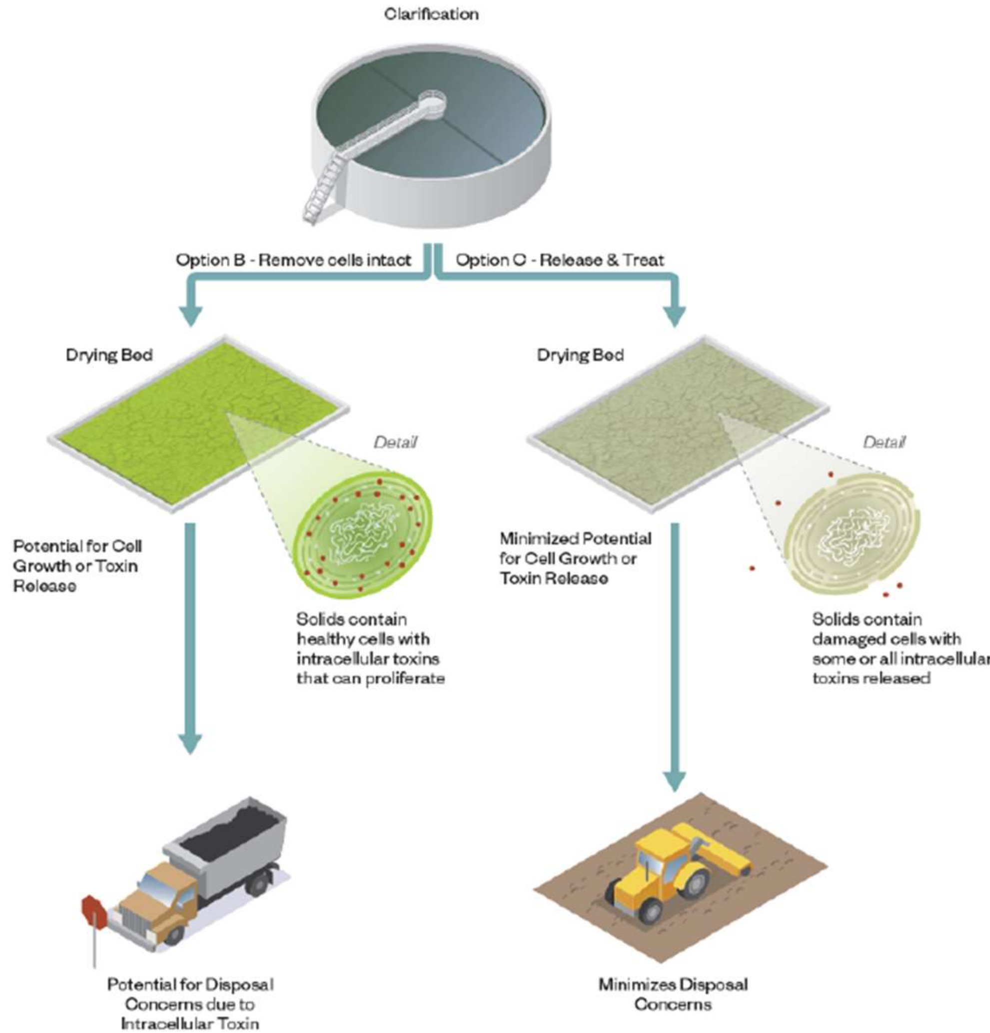
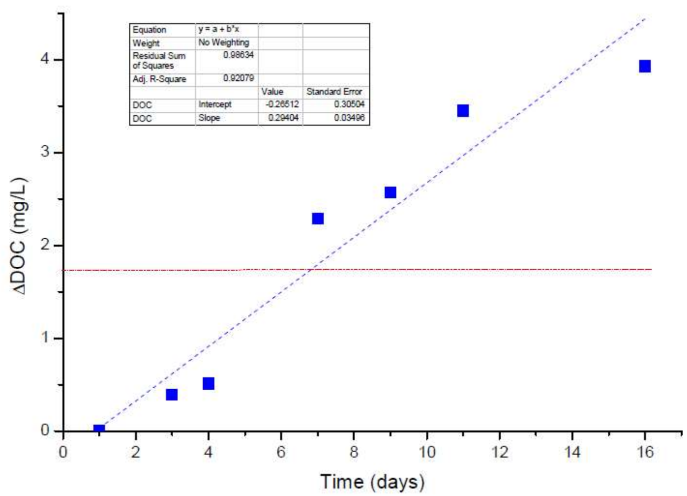
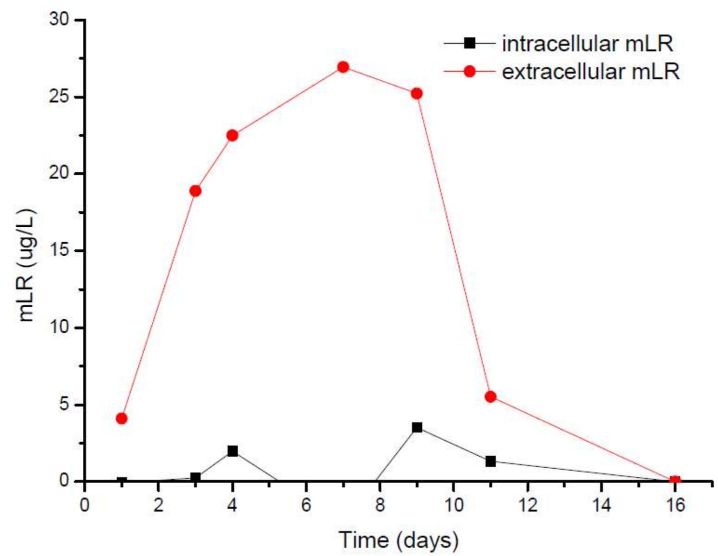


Figure 11. Potential Impacts of Cyanobacteria on WTP Residuals Management

Fate of cells and metabolites after coagulation in sludge:



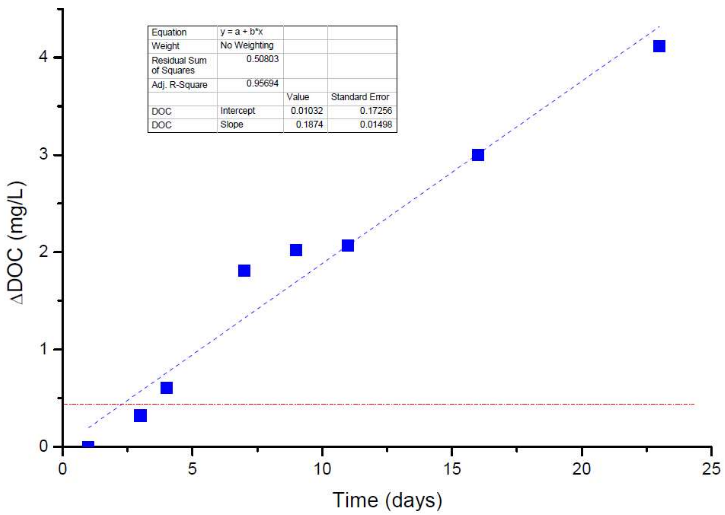
RESULTS: INCREASE OF DOC CONCENTRATION WITH TIME; MYPONGA WATER AND CULTURED *M. AERUGINOSA*. RED DOTTED LINE REPRESENTS MAXIMUM EXPECTED INCREASE FROM CELL LYSIS ALONE.



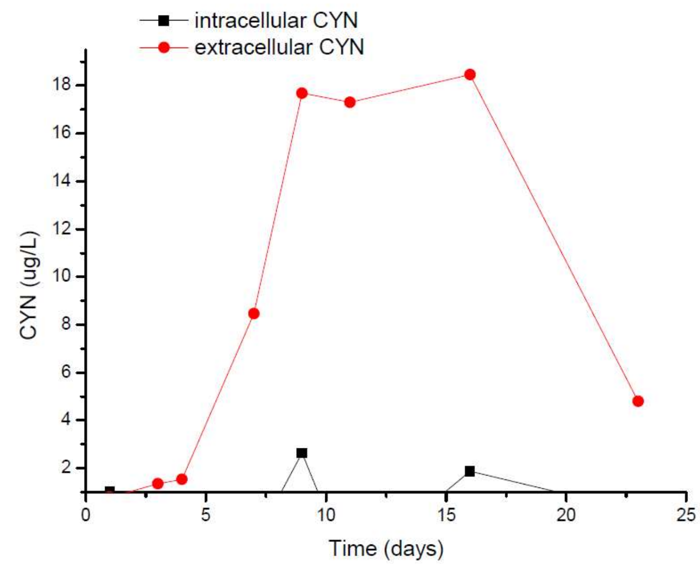
Results: Concentration of MC-LR as a function of time in days; Myponga water and cultured ***M. aeruginosa*****.**

Similar results for MC-LA.

Fate of cells and metabolites after coagulation in sludge:



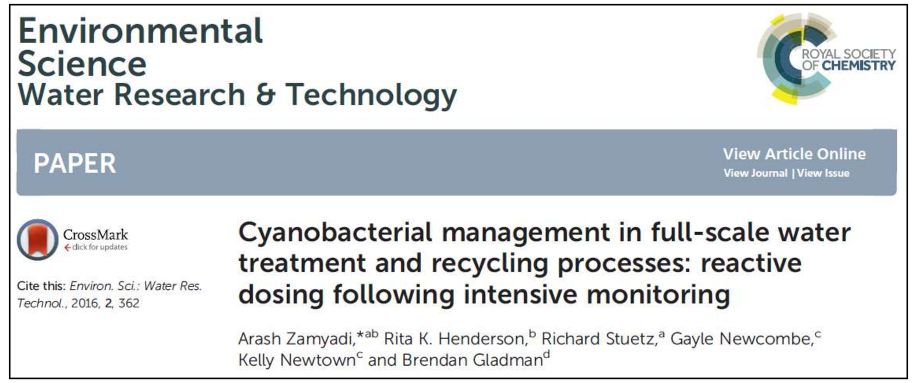
RESULTS: INCREASE OF DOC CONCENTRATION WITH TIME; MYPONGA WATER AND CULTURED *C. RACIBORSKII*. RED DOTTED LINE REPRESENTS MAXIMUM EXPECTED INCREASE FROM CELL LYSIS ALONE..



Results: **Concentration of cylindrospermopsin (CYN) as a function of time in days; Myponga water and cultured *C. raciborskii*.**

Single point use:
Cyanobacterial cell accumulation in the sludge;

Example of treatment adjustment used by Melbourne Water: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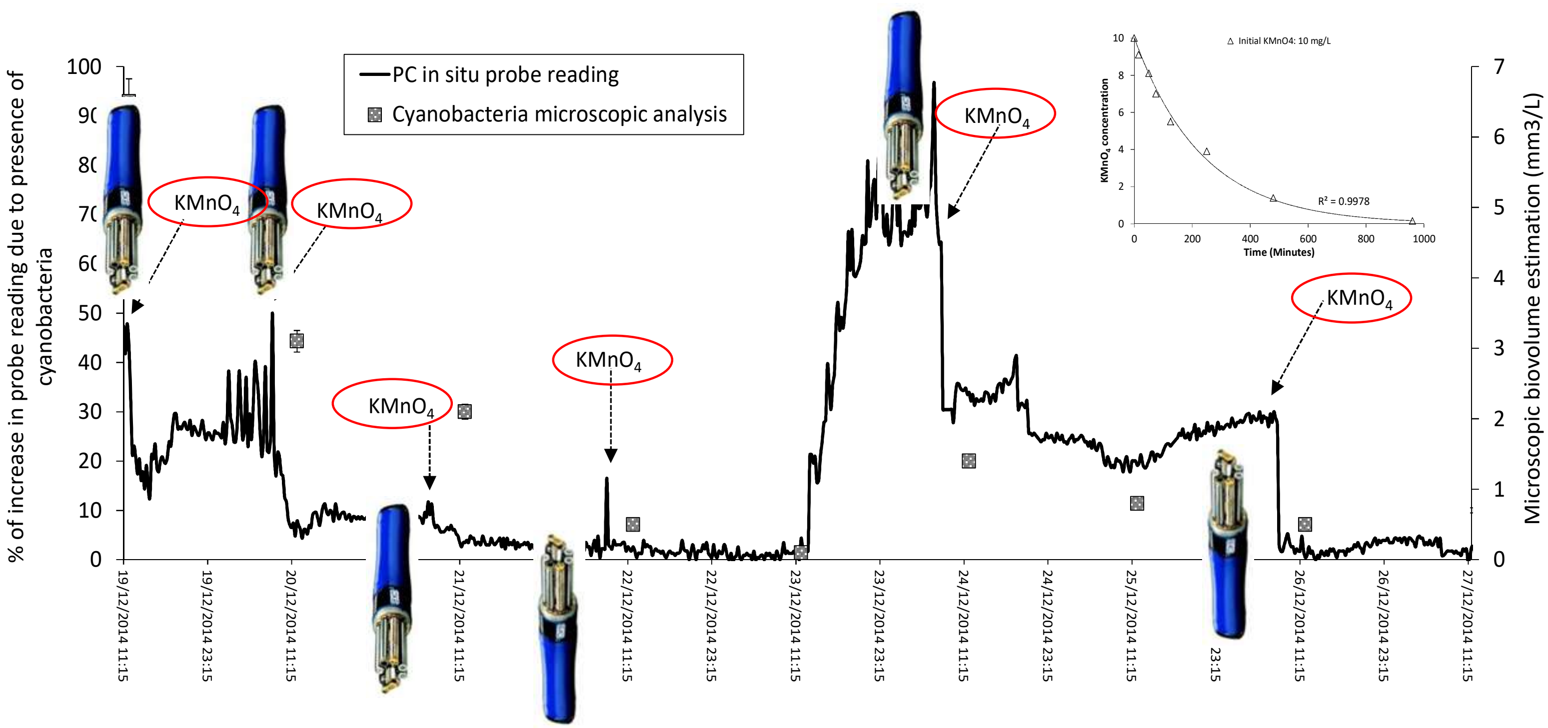
Cyanobacterial management in full-scale water treatment and recycling processes: reactive dosing following intensive monitoring

Arash Zamyadi,*[ab] Rita K. Henderson,[b] Richard Stuetz,[a] Gayle Newcombe,[c] Kelly Newtown[c] and Brendan Gladman[d]



Application of GAC for removal

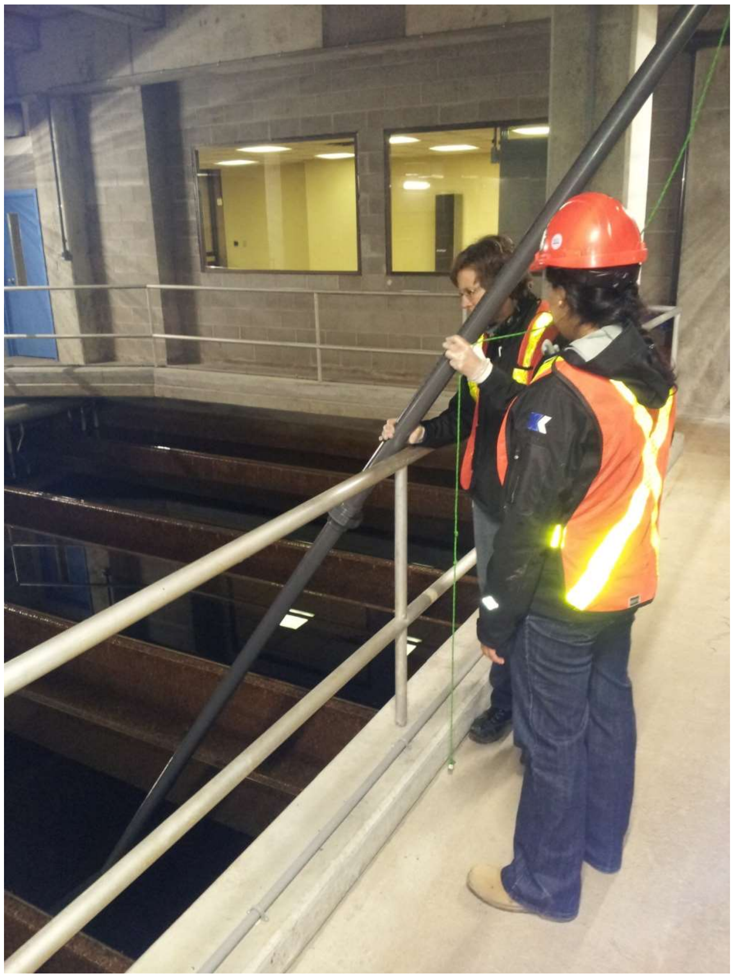
22 column pilot setup - Lorne Park WTP - Ontario

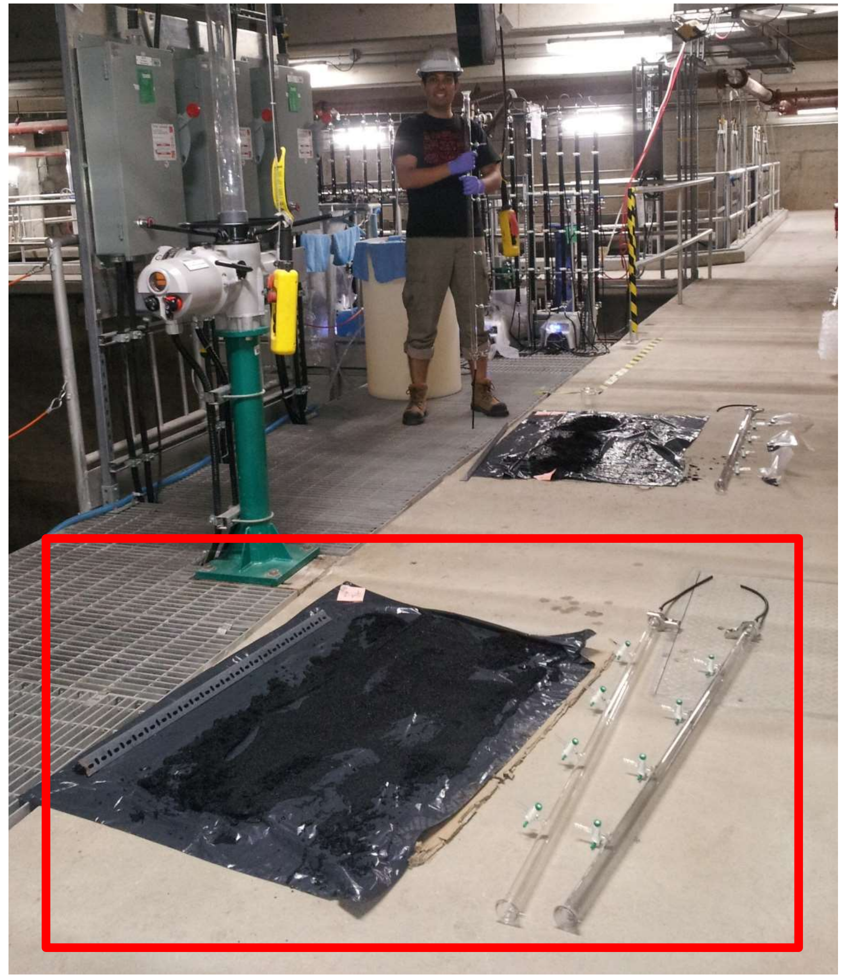
Assessing the remaining service life of full-scale GAC for H_2O_2 quenching and T&O compound removal

22 Column Pilot Set-up at Lorne Park WTP

Application of GAC for removal

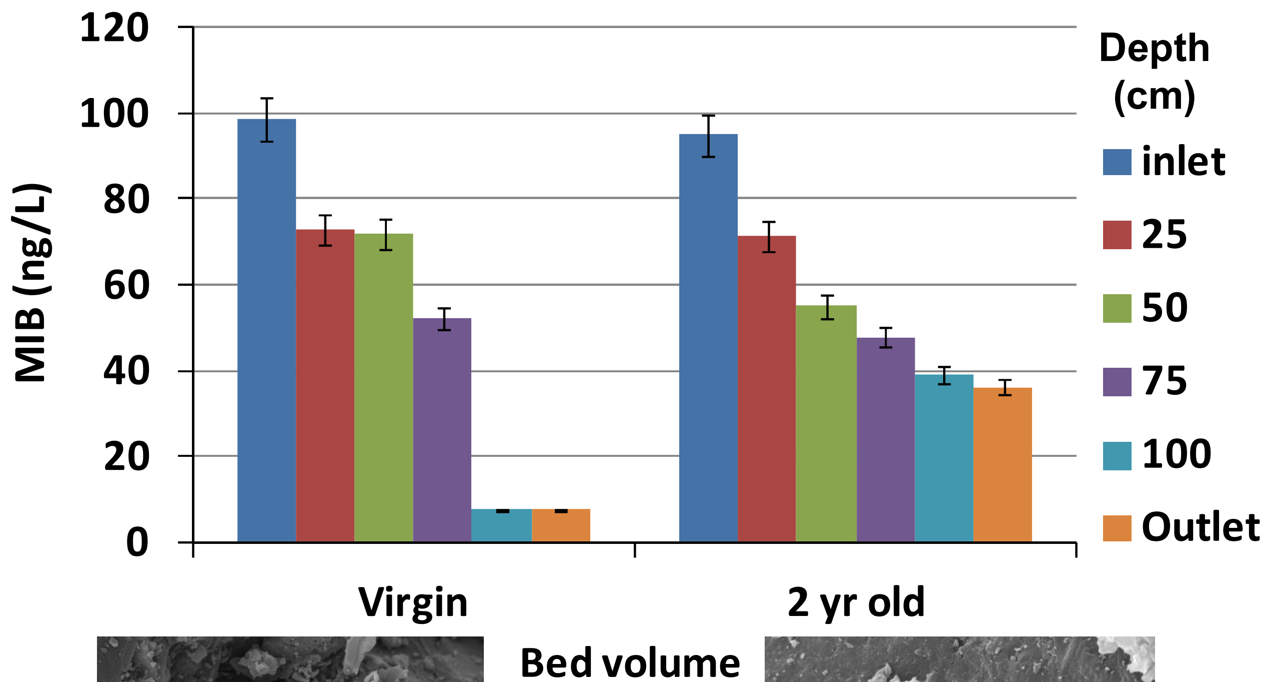
Colum preparation: GAC sampling from the full-scale contactors

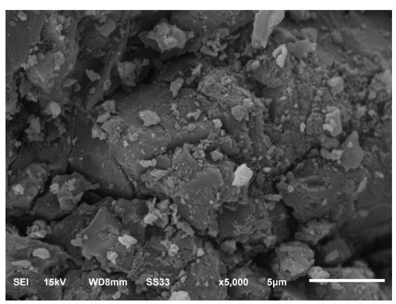


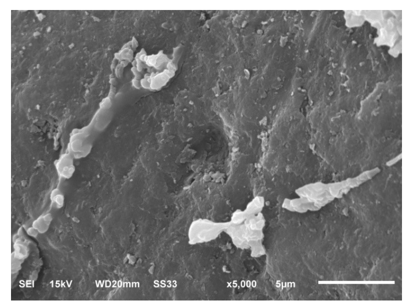


Application of GAC for removal MIB

MIB removal using full-scale & virgin centaur GAC
(similar results for 1 year old GAC and geosmin)

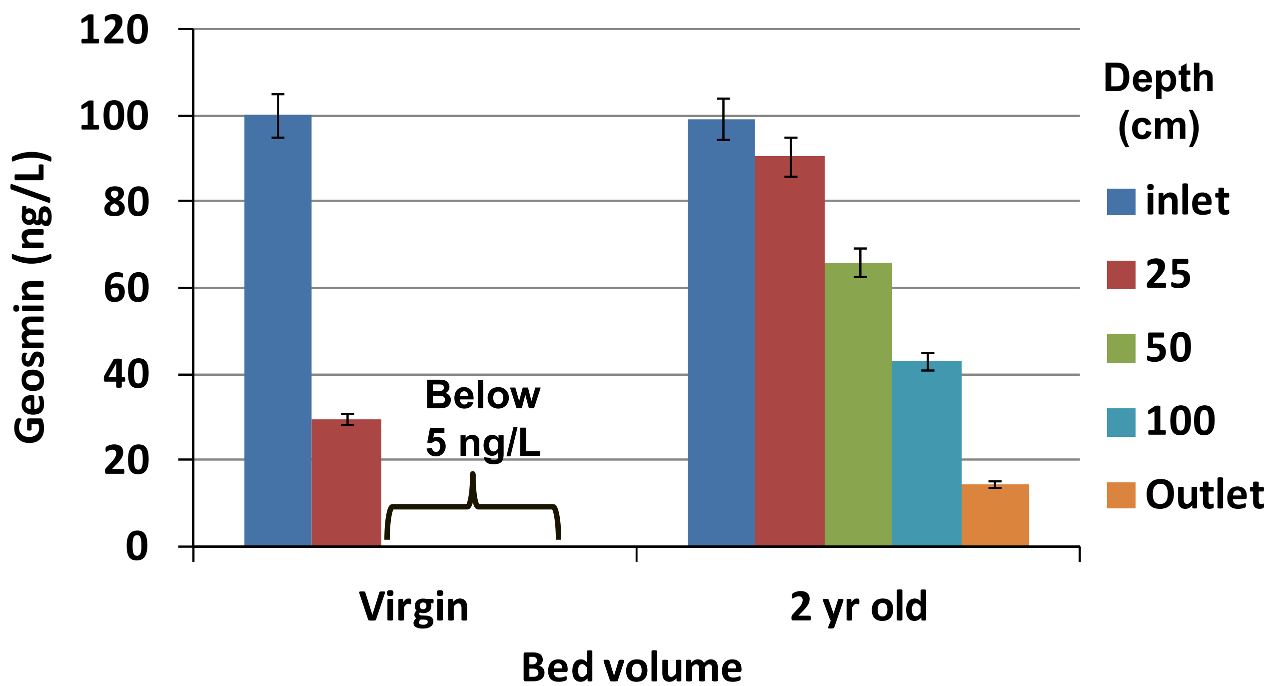






Application of GAC for removal geosmin

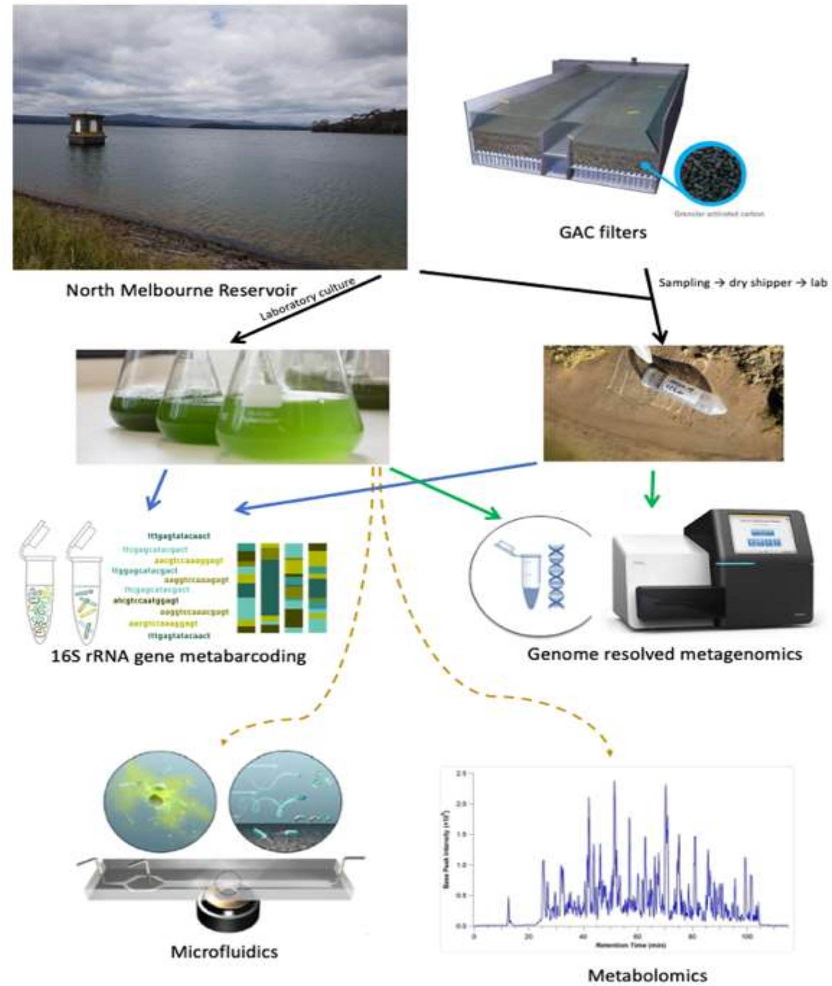
Geosmin Removal Using Full-scale & Virgin Centaur GAC



Ongoing work: Understating BAC

Assessment package for Melbourne Water:

- **Identity potential functions of cyanobacteria in the reservoir, as well as the BAC biofilm communities with focus on stagnation**
  - PhD student at University of Melbourne funded by an ARC Discovery Gant
  - Supervisors: Linda Blackall, Dug Romney, Arash Zamyadi (Melbourne), Jillian Banfield (University of California Berkeley)

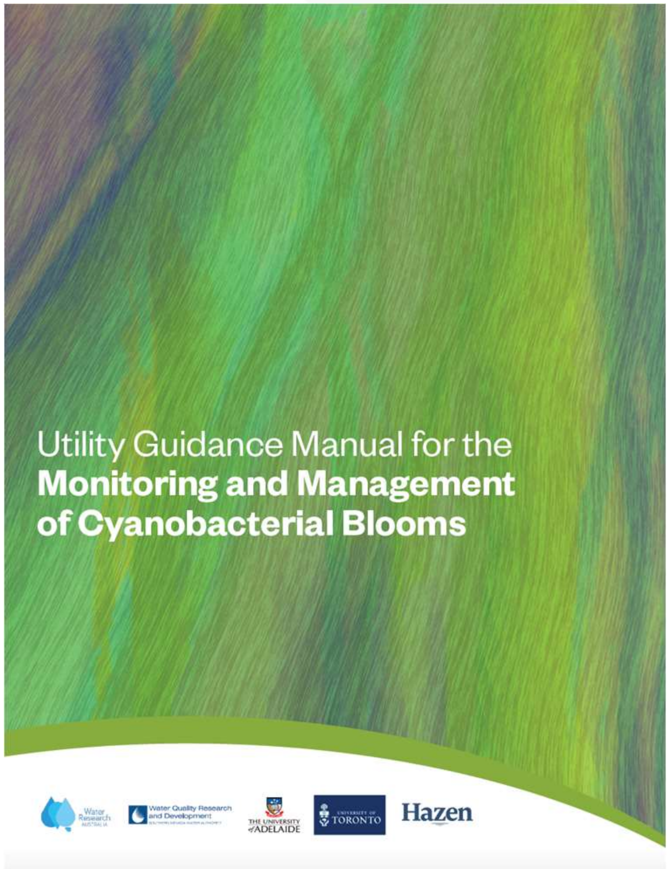


WATER RESEARCH FOUNDATION (#4912)

- "Developing Guidance for Assessment and Evaluation of Harmful Algal Blooms, and Implementation of Control Strategies in Source Water"

- Project Team
  - SNWA – Faith Kibuye, Eric Wert (PI)
  - Water Research Australia– Arash Zamyadi (coPI)
  - University of Adelaide – Virginie Gaget (coPI)
  - Hazen – Christine Owen (coPI)
  - University of Toronto – Ron Hofmann, Husein Almuhtaram

- https://www.waterrf.org/research/projects/developing-guidance-evaluation-and-implementation-control-habs-source-water
- https://www.waterra.com.au/research/communities-of-interest/algal-innovation/



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