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Understanding the intersecting social, technical, and ecological systems challenges associated with emerging contaminants in drinking water using cyanotoxins as an example

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Abstract

This paper investigates toxic algal blooms (TABs) and their management as an example of a complex emerging contaminant (EC) problem through the lens of interconnected social, technical, ecological systems (SETS). We use mixed methods including analysis of a national survey of public drinking water systems and interviews with drinking water managers and state regulators. For the first time, we extend SETS to the drinking water context to advance a holistic understanding of the complexity of TABs as a problem for drinking water systems and identify specific intervention points to ease TABs management difficulty. We find that management challenges arise at the intersection of SET domains, and often coincide with circumstances where water managers and existing technologies are pushed outside of their traditional operating spheres or when new technologies are introduced creating cascading SET challenges. ECs that do not behave like traditional contaminants and pollutants require adapting social and technical systems to be responsive to these differences. Understanding how management difficulties arise within SET domains and their intersections will help drinking water managers and state regulators mitigate management difficulties in the future. These findings have implications for understanding and mitigating other EC management challenges as well.

Keywords Emerging contaminants, Cyanotoxins, Socio-technical systems, Socio-ecological systems, Global environmental change

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Introduction

Emerging contaminants (ECs) like algal toxins, 1,4-Dioxane, 1,2,3-tricholoropropane, nanoparticles, mircroplastics, plasticizers, and pharmaceuticals [68] are ubiquitous and proliferating globally [78]. ECs in drinking water may have adverse health effects on humans but are not regulated in water law [57, 77]. ECs are difficult to manage because they often do not conform to the patterns of existing regulations and analytical techniques aimed at detecting traditional drinking water pollutants [72]. For example, ECs have the potential to transform and be transported long distances, creating unforeseen and uncharacterized chemicals in areas distant from the source (Machado et al. 2016) whereas drinking water regulations focus mostly on specific pollutants and contaminants not derivatives or mixtures of chemicals and on protecting source waters from local sources of pollution. ECs are also challenging because they differ from traditional contaminants making them difficult to remove using conventional drinking water treatment technologies and management practices [32, 75]. Common treatment processes including filtration (sand, activated carbon) and disinfection (chlorine, ozone) are ineffective or only partially effective at removing ECs [11, 26, 31, 73]. In some cases, conventional drinking water treatment practices may make ECs worse. For example, chemicals used in disinfection can increase the formation of antibiotic-resistant bacteria and genes [49, 87].

Calls for greater understanding and management of ECs in drinking water have advanced understanding. But, most of this understanding is focused on the technical and to some extent the ecological dimensions (e.g., better detection, treatment and removal technologies, environmental fate and transport, respectively) [3, 5, 9, 38, 56, 64, 65, 69, 79, 80, 82]. The human dimensions and their intersections with technical and ecological dimensions have largely been ignored. For example, while research examines the prevalence of antibiotic-resistant organisms in the environment and whether drinking water systems (DWS) remove them [23, 49, 87], there is less understanding of how farmer decisions, politics, and markets interact to increase antibiotic use leading to the proliferation of antibiotic-resistant organisms in the first place [44]. Moreover, there is very little to no work that we know of concerning managers at DWS and how they make decisions or think about ECs management. And while there is increasing recognition of the need for understanding human dimensions of ECs and DWS [42, 43], there is very little actual progress.

We argue a more holistic approach to understanding ECs and their management in DWS is urgently needed. To begin to fill this gap we apply a social, technological, and ecological systems (SETS) [27, 50, 52] lens to explore different dimensions and their interconnections using algal toxins as an example. While scholars have begun to think about infrastructure, particularly urban stormwater and flood control systems, as complex, interdependent SETS [27, 50, 52], to the best of our knowledge, this is the first application of SETS to DWS.

Water infrastructure as complex, interdependent SETS

SETS emerged to more fully explain infrastructure dynamics and failures stemming from the un-designed, non-linear relationships that emerge when one part of the system (often the technological) is optimized without consideration of the dynamics between technical, social, and ecological dimensions which collectively impact system performance [50, 81]. This emergence coincided with a broader evolution in thinking of infrastructure as more than technological systems and as a primarily human construct [30, 45, 48, 50].

SETS evolved from two streams of scholarship: one focused on sociotechnical systems (STS) and another focused on social-ecological systems (SES). Fundamentally, STS views social processes and technology as mutually constructive, interacting to shape and reshape each other in myriad ways [6, 10, 39]. While STS deeply engages social and technological functions and dynamics, STS largely ignores ecological dimensions [2]. SES emerged from collaborations between scholars in ecology and political science seeking to explain unsustainable outcomes in the management of natural resources through the lens of complex adaptive, multilevel systems [4, 8, 35, 46]. While SES scholarship engages ecosystem functions and dynamics and social processes equally, technological dynamics are left to the sidelines [2]. SETS brings these dimensions together arguing that technology shapes and is shaped by human–environment relationships. This view opens the possibility of approaching questions not addressed in SES or STS, such as how system pressures in complex SETS are linked and how socio-technical dynamics affect and are affected by environmental or socio-environmental dynamics [2].

In defining SETS, social systems (S) include actors, values, knowledge and practices, policy, governance, and related components, while ecological systems (E) include natural resources, pollution, and ecological structures, functions and behaviors [33]. Finally, technological systems (T) include physical and cyber infrastructure, expert knowledge, and decision-support (Graboswki et al. 2017). In addition to S, E, and T, there are intersections between socio-technical (S-T), socio-ecological (S-E) and technical-ecological (T-E) dimensions representing both interconnectivity as well as mutual constructions as one-dimension shapes another and vice versa. Figure 1 is our conceptual model showing DWS

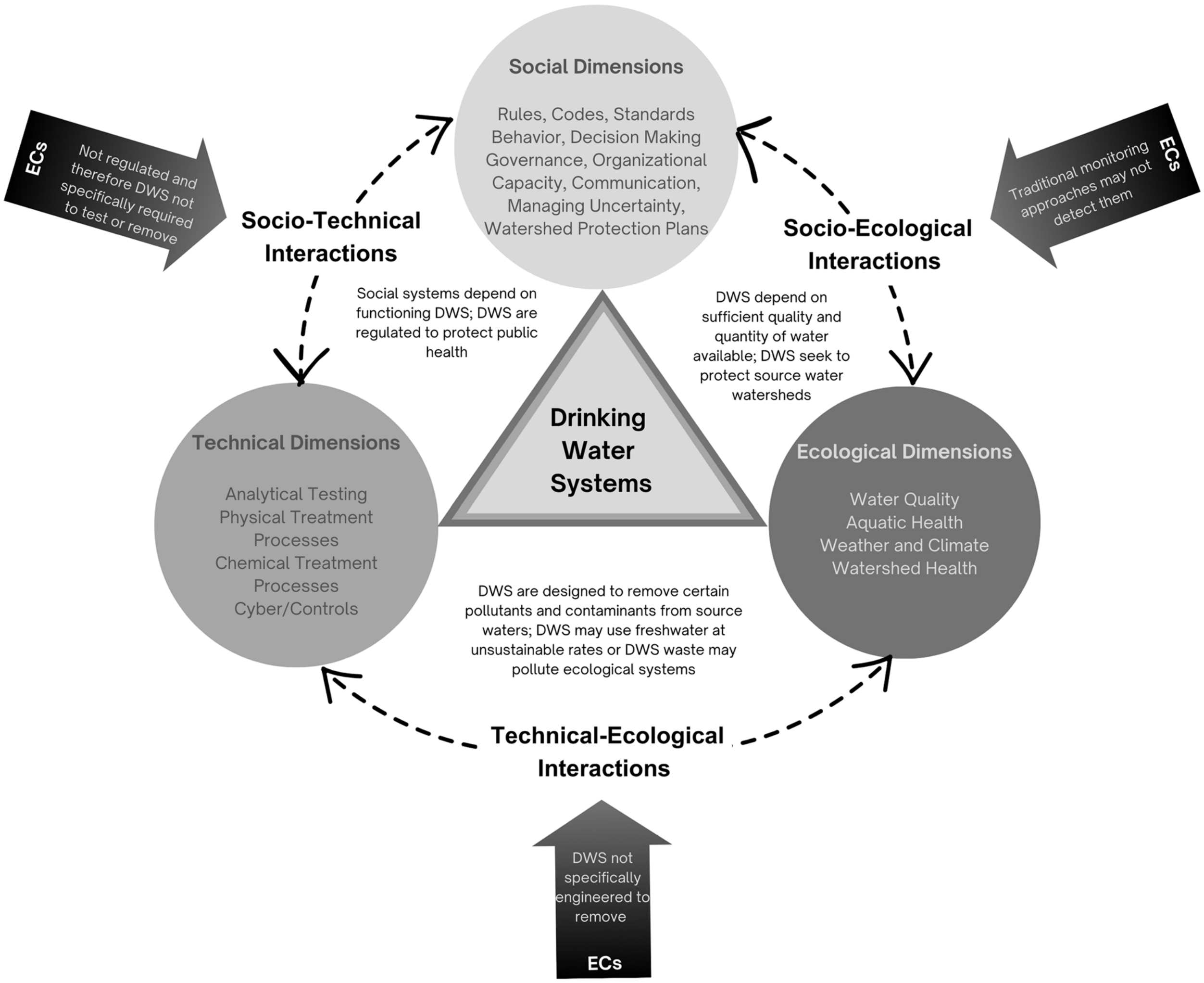

Fig. 1 Overview of drinking water systems as interconnected social, technical, and ecological and systems (SETS). The arrows at each socio-technical, socio-ecological, and technical-ecological interaction describe how emerging contaminants (ECs) may impact DWS. Figure adapted from Markolf et al. [50]

as SETS and illustrating (with arrows) how a SETS lens may be useful to explore how ECs might impact DWS. As illustrated, starting with S-T interactions, ECs may not be regulated and therefore DWS are not required or engineered to remove them nor are DWS required to monitor for them and existing monitoring approaches may not detect them in source or treated water (respectively, the S-T, T-E and S-E interactions).

Toxic algal blooms and drinking water

The occurrence of harmful algal blooms (HABs), which include both nuisance and toxic algal blooms (NABs and TABs) in surface water bodies, is increasing worldwide [37, 62, 63]. Many of these surface waters experiencing HABs are used as a water source for DWS. NABs cause taste and odor problems but are generally harmless to humans. TABs are caused by organisms, most often cyanobacteria, that release toxic chemicals; these toxins, considered a category of ECs, negatively affect both human and environmental health [7, 14, 15, 24, 25, 40, 41, 55, 60] (Richardson and Kimura 2017). Despite the presence of TABs in drinking water sources [3, 9, 75] and in treated drinking water [16, 19, 28, 38], there is no uniform federal drinking water regulation for algal toxins in the US.

While the US federal government (e.g., USEPA) does not regulate cyanotoxins, TABs outbreaks in drinking water in Ohio and Oregon [13, 41, 55] prompted state action. In Ohio, TABs noticeably increased from 2007 to 2012 prompting the state's Environmental Protection Agency (OHEPA) to initiate drinking water testing for the algal toxin microcystins (see "US State TABs regulations for DWS" section in 2011 (OHEPA 2022). Microcystin testing alerted officials to problems in Carrol Township in 2013 and Toledo in 2014 when cyanotoxins were detected in the finished water. Four years later, the same problem happened in Salem, Oregon. In all three cases, the DWS shut down temporarily to protect public health [13, 41, 55]. These outcomes were predictable. Research shows that existing drinking water infrastructure—whether consisting of conventional or more advanced treatment systems—may be incapable of completely removing algal toxins [9, 38, 85, 86] and other ECs more broadly [47].

We know that TABs, like other ECs, are difficult to manage [75]. While TABs management challenges encompass multiple dimensions, research tends to focus on a single dimension at a time ignoring important intersections and potentially missing critical insights. Research on the social dimensions of cyanotoxins in DWS beyond the health impacts is particularly scarce. We aim to fill this gap by learning from regulatory staff and DWS managers in states with and without TABs regulations who have experience with different cyanotoxin monitoring, treatment, and reporting requirements. Specifically, we use a SETS lens to gather and analyze data to answer the question how do human, environmental (e.g., EC behavior), and technical factors and their interconnections influence TABs management?

This paper is organized as follows; "US State TABs regulations for DWS" section provides a brief overview of US state TABs regulations. We describe our mixed methods in "Methods" section and present our findings in "Results" section. Finally, in the conclusion we include practical advice for drinking water regulators and managers on how to improve TABs and ECs management and response, and suggest areas for future research.

US State TABs regulations for DWS

Three U.S. states regulate cyanotoxins, at least partially. These states set regulatory limits (Table 1), require cyanotoxin monitoring and often recommend (or require) specific analytical methods for detecting cyanotoxins (Table 2). These analytical detection methods include approaches such as enzyme-linked immunosorbent assay (ELISA), quantitative real-time polymerase chain reaction (qPCR), and liquid chromatography with tandem mass spectrometry (LC–MS-MS) [14, 15, 36, 60, 83].

Methods

We use mixed methods combining data from a previously conducted a survey [75] with semi-structured interviews to understand the experiences, management approaches, and management challenges with TABs across DWS in states with and without TABs regulations. We gather and analyze these data using a SETS lens to answer the question how do human, environmental, and technical factors and their interconnections influence TABs management? Prior to conducting the research, we secured University of Michigan Institutional Review Board approval under HUM00148793. The research was conducted in accordance with the ethical principles for respect for persons, beneficence and justice. Respondents provided verbal consent prior to initiating research.

Survey

We collected data through an online Qualtrics survey (Qualtrics, Provo, Utah) of U.S. public DWS previously described in Treuer et al. [75]. For the survey, we identified DWS using the USEPA's Safe Drinking Water Information System database focusing on those that primarily use surface water. In total, 355 water managers from 42 U.S. states responded out of 3,067 contacted. The 12% response rate is typical for self-selecting surveys [74]. Despite the low response rate, respondents were

Table 1 Cyanotoxin thresholds/health advisory levels for treated drinking water in Ohio, Oregon, and Rhode Island, U.S

Region	Total Microcystins (μg/L)	Cylindrospermopsin (μg/L)	Anatoxin-a (μg/L)	Total Saxitoxins (μg/L)	Reference(s)
Ohio	0.3[a,b] 1.6[c,b]	0.7[c] 3.0[a]	0.3[c] 1.6[a]	0.3[c] 1.6[a]	[58]
Oregon	0.3[a] 1.6[c]	0.7[c] 3.0[a]	none	none	[59]
Rhode Island	0.3[e]	1[e]	20[e]	0.2[e]	[66]

[a] Children less than six years old and sensitive populations

[b] Action Level

[c] Children six years old or more and adults

[d] Infant formula

[e] Maximum Contaminant Level

Table 2 Cyanotoxin monitoring requirements Ohio, Oregon, and Rhode Island, U.S

State/Province	Cyanobacteria monitoring and cyanotoxin testing requirements for PWSs	Reference
Ohio	Routine testing (weekly, biweekly, or monthly depending source water microcystins occurrence) of source water for toxin-production genes (i.e., indicating cyanobacteria present are capable of producing microcystins, cylindrospermopsin, total saxitoxins, or anatoxin-a) is required using qPCR[a], followed by cyanotoxin testing using ELISA[b] if toxin-production genes are present. Cyanotoxin testing using LC–MS/MS[c] is required if detections are greater than 50% of the toxin threshold	[58]
Oregon	Biweekly testing of source water for cyanotoxins (i.e., microcystins and cylindrospermopsin) is required from May 1 through October 31 using ELISA, or another EPA-approved method that applies at the time samples are analyzed. Weekly testing is required if cyanotoxin concentrations are ≥ 0.3 µg/L. For cylindrospermopsin, if detections greater than 0.7 µg/L are found, samples must be analyzed using LC–MS/MS, or another EPA-approved method that applies at the time samples are analyzed	[59]
Rhode Island	Daily visual monitoring of source waters is required from May through October. Weekly cyanobacteria screening for genera present and cell count or biovolume information is required if the DWS determines it necessary. Toxin testing (i.e., for microcystins, cylindrospermopsin, total saxitoxins, or anatoxin-a) ELISA or LC–MS/MS may be required by the RI Department of Health Director on a case-by-case basis. Toxin analysis using LC–MS/MS is required if total microcystins exceed the Maximum Contaminant Level	[66]

[a] Molecular quantitative polymerase chain reaction (qPCR)

[b] Enzyme-linked immunosorbent assay (ELISA)

[c] Liquid chromatography with tandem mass spectrometry (LC–MS/MS)

representative of the population of DWS based on ownership type and size (population served).

The survey consisted of both multiple choice and open-ended questions on water system characteristics (e.g., population served, water source) and their experience managing NABs and/or TABs. Water managers were asked if and how often they experience TABs and NABs events (never, rarely, once every 2–3 years, 1–2 times a year, more than twice a year, total number of years), when blooms typically occur (with instructions to select typical months during the year), and for how long (i.e., how many days blooms typically last). Water managers were also asked about TABs management and response including where they sample for cyanotoxins (i.e., at the intake, at multiple depths, at multiple locations), if they have an algal bloom response plan, and what strategies they use to manage algal blooms (i.e., watershed management, preventative measures in the source water, in source treatment, and in plant treatment). Finally, water managers were asked to describe their management strategies in more depth in an open-ended response question. NABs and TABs were defined for participants before the start of the survey. NABs were defined as, “blooms that negatively impact the taste, odor, oxygen levels, and/or appearance of water bodies but that do not have high levels of harmful toxins”. TABs were defined as those that, “occur when certain organisms, most often cyanobacteria, grow out of control and release toxic chemicals into the water. Toxins typically produced include microcystins, cylindrospermopsin, and anatoxin-a”.

We refer readers to Treuer et al. [75] for detailed quantitative survey results summarizing how many DWS experience TABs, how often, and manager perceptions about whether TABs are getting worse and if they feel prepared to handle TABs. Here we use the survey as follows: 1) to identify interviewees (among those that experience TABs, see "Interviews and Qualitative Data Analysis") and "US State TABs regulations for DWS" sections) to analyze responses to survey questions that have not been analyzed previously including open-ended questions about strategies managers use to respond to HABs and providing a more nuanced understanding of the interaction between TABs experience and TABs management difficulty. We describe how we analyzed these data in the next section and interweave the quantitative survey results with the qualitative interviews in the results.

Survey data analysis

We used bivariate statistical tests (chi-square and t-tests) to understand relationships between the type of HABs experience (TABs experience, NABs experience, and no experience) and responses to HAB events (e.g., monitoring and management strategies). For the open-ended question, two co-authors independently coded responses into fifteen management categories (e.g., Change Source, Selective Withdrawal, Prevent in Lake, Use Algaecide, Conventional Treatment, Adjust Flow, Oxidize, Permanganate, Chlorination, PAC, Use Advanced Technology, Nutrient Management, Increased Sampling, Clean Filters, None) to understand the diversity of management options used for NABs and TABs. The categories were developed inductively based on common management strategies described by survey respondents in their open-ended responses [12, 54, 67] and were detailed in a codebook [20] (see Supplemental Information). We assessed intercoder reliability in two ways– consistency of judgment over absence and presence and consistency of judgement across the two independent coders. Results indicated > 95% agreement and were deemed satisfactory [12, 54, 67].

Interviews and qualitative data analysis

Between May and August 2019, we carried out 24 in-depth interviews with water regulators (from five US states and one Canadian province) and water managers (from seventeen water systems across eight U.S. states with and without cyanotoxin regulations) using an interview guide (see Supplemental Information). Interviews helped us understand in more depth the challenges and complexities of TABs management and response using a SETS lens. We identified water regulators through internet searches in states with TABs regulations and then snowballed to have representation from states with and without TABs regulations. We identified DWS interviewees through a random sample of our survey respondents who indicated they had TABs experience and via snowball sampling of interviewees. We aimed for variation in TABs experience, geographic coverage, and population served among the interviewees. In total, we identified and contacted 61 individuals from 22 different U.S. states, of which, 24 agreed to be interviewed, a 39% response rate.

We conducted interviews by phone, lasting on average 42 min (ranging from 17 to 70 min). We asked state regulators about their state's overall TABs experience, cyanotoxin regulations, if applicable, ease or difficulty in managing TABs, using follow-ups as needed to probe for human, environmental and technical difficulties (or lack thereof), and amount and type of collaboration with different entities around TABs management. Collaboration was theorized to ease TABs management in prior research [75]. We asked water managers at DWS about their TABs experience, concerns, and ease or difficulty in managing TABs as well as about the regulatory environment for cyanotoxins, including cyanotoxin monitoring, testing and treatment. As with state interviewees, we used follow-ups as needed to probe human, environmental and technical difficulties (or lack thereof). We report evidence from interview and survey respondents using codes, where S = state interviewee, SU = survey respondent, and U = drinking water manager, followed by numbers to indicate the first, second, or third interviewee or survey respondent.

We recorded and transcribed [29] the interviews, and then two authors independently reviewed and coded the transcripts using qualitative data analysis software NVIVO 11 (QSR International, Burlington, Massachusetts, USA). Intercoder reliability was assessed in the same way as previously described for coding of open-ended survey questions and likewise determined to be satisfactory (> 95% agreement) [12, 54, 67]. In addition to general questions about TABs experience, we coded responses to the following questions: In your opinion, how difficult is it to manage or remove cyanotoxins? Have you experienced any challenges in monitoring or testing for cyanotoxins in your source water? If so, how have you addressed those challenges? Have you encountered any issues in communicating with the public or regulators about cyanotoxins? Themes emerged during coding spanning a range of technological (monitoring and treatment), social (perceptions of difficulty, regulatory compliance, knowledge, communication), and ecological (organism behavior) dimensions as well as interconnected challenges and solutions (for the codebook, see Supplemental Information).

Results

DWS managers with and without TABs experience

About a fifth the 355 water systems in our sample experienced TABs [75], these managers reported TABs occur for 3.0 ± 1.7 months per year typically from July through September. Water managers also reported that when TABs occur, they last anywhere from 1 to 120 days with a median of 14 days.

Of the 18 DWS managers interviewed, the majority (77.8%) experienced TABs including not just in their source water but also within the water treatment plant (12 of 18) and in the finished water (1 of 18). Of the fourteen interviewees with TABs experience, eight DWS managers detected total microcystins in their source waters, making microcystins the most detected cyanotoxin. Two managers detected cylindrospermopsin, two detected anatoxin-a, and only one DWS manager detected saxitoxin. Three additional water systems reported that they detected cyanotoxins in their source water but did not identify a specific toxin.

Interviews with six state water regulators painted a similar picture with microcystins being the most frequently detected cyanotoxin followed by cylindrospermopsin. One state regulator reported 60% of systems found microcystin in the raw water while another state reported that 8 out of 10 DWS asked to test for microcystin found the cyanotoxin in their source water. The following sections use the interview and survey data to describe in detail the SETS challenges water managers face in dealing with TABs and how water managers address those challenges.

Social dimensions and intersecting socio-technical and socio-ecological dimensions

Regulations that establish toxin limits can both help and hinder TABs management. Some water managers in states with cyanotoxin regulations (e.g., Oregon and Ohio) reported challenges with regulatory compliance early on, specifically in soliciting help from state regulators to aid in compliance– "*…it was like the blind leading the blind*" (U3), and in keeping up with the frequency of regulatory changes (U6). Surveyed water managers agreed with this general lack of expertise at the state on how to handle HABs (SU19). Also, because cyanotoxin regulations usually focus on either total microcystin or microcystin-LR, other toxins (e.g., microcystin cogeners, cylindrospermopsin, anatoxin-a, and saxitoxin) are not regulated. This is a challenge because DWS managers detect not only regulated toxins like microcystin and cylindrospermospin in source waters, but also unregulated ones including anatoxin-a or saxitoxin (U18). Other water managers reported regulations provided certainty that helped ensure public trust in the safety of their water supplies. For example, water managers reported that new cyanotoxin regulations help by providing a limit (U7), which gives, "*…water customers more confidence that their drinking water is safe to drink*" (U4). Table 3 summarizes how social interventions (e.g., regulations) impact TABs management difficulty across social, socio-technical, and socio-ecological dimensions.

Along with establishing limits for cyanotoxin in drinking water, regulations also establish requirements for cyanotoxin monitoring and reporting (Table 2) that can make management more (or less) difficult. On the one hand, management is more difficult because cyanotoxin monitoring is not as easily incorporated within the standard contaminant monitoring framework for DWS and because monitoring does not always yield predictable results. Water managers test for cyanotoxins more frequently than is normally required for other chemicals and toxins (S2). Among surveyed systems, water managers with TABs experience did more routine sampling (i.e., at multiple depths and/or at multiple locations) than systems with NABs or no HABs experience (i.e., limited sampling to one location, the water treatment plant intake) ($\chi^2=22.641$, $N=355$, $p<0.0001$). Despite all the monitoring, for most (88%) of surveyed water managers, monitoring results did not yield clear information for TABs management. Statements from managers range from being unable to detect distinct patterns to predict if a bloom will produce toxins (U9), to knowing very little about when toxins are produced (S6) and struggling to understand species' type as source water quality is dynamic (U2). For example, managers mentioned that, *"If you take five different samples in the lake, you will get five different readings. Toxin levels vary greatly from location to location"* (U4), or "…[toxin levels are] *never the same in two different places"* (U7),*"… you could have a bloom that's toxic, and one right down the lake from it that's not toxic…"* (U14), and a bloom can happen "… *overnight and then suddenly [there is] a toxin in the source water*" (S1). Results exemplify the difficulty in using current monitoring protocols and tools to predict when blooms occur, which species will dominate a bloom, and if the organisms present will produce toxins.

But regulations requiring monitoring could also ease management difficulty partly because some managers are able to invest in improved monitoring equipment and are able to learn from experience from monitoring over time. State regulations enabled investment in cyanotoxin management and response such as improving lab testing methods (U18) or access to equipment – specifically, qPCR (quantitative polymerase chain reaction) (U3) to help determine if the cyanobacteria present can produce toxins or not. Managers in states without regulations are less able to justify the costs to improve TABs management without a regulatory push (U13). Accumulating data over time also helps. Two managers described using phycocyanin fluorescence, a technique that detects light emission from phycocyanin [60], a pigment in cyanobacteria and an indicator of cyanobacteria biomass. *"Phycocyanin seems to be a big indicator of harmful algae… what we've seen over the past three years is that every time our phycocyanin level actually gets above the chlorophyll level in the raw water…* [we] *see a spike in our microcystin… in our raw water"* (U15). Another used microscopy to identify and quantify algal species over time to understand when certain species present at certain amounts are associated with cyanotoxin detection. Eventually one can begin to detect toxins at certain levels and establish thresholds for future monitoring (U6). Ongoing monitoring of TABs over time may help some managers understand organism behavior and improve management; however, this may be context specific and counter intuitive. For example, we found that DWS that experienced TABs more often (once every 2–3 years or more often) versus rarely, reported TABs as more difficult to manage ($\text{mean}=7.44$) compared to those who experienced them less often ($\text{mean}=6.24$, $p<0.05$).

In addition to anticipating whether a bloom will produce cyanotoxins or not, water managers need to recognize if the toxin is intra- or extra-cellular to inform treatment decisions [21]. While some water managers are equipped to identify whether the toxin is intracellular or not and conduct tests weekly to make this determination (U12), others lack this capacity (U17). Water managers who can identify where the toxin is either inside or outside the cells use that information to make decisions about their treatment process and whether the goal is to remove the toxins or to remove the cells (U17). Conversely, water managers who cannot distinguish intra- or extra-cellular toxin, must be conservative

Table 3 Interventions in the social dimension (regulations) increase or decrease TABs management difficulty across social, socio-technical, and socio-ecological dimensions

	Interventions	Social Dimensions		Technical Dimensions		Ecological Dimensions	
		Management Difficulty		Management Difficulty		Management Difficulty	
		Increased	Decreased	Increased	Decreased	Increased	Decreased
Social Dimensions	Regulations that set limits for cyanotoxins	• If both state regulator and DWS are learning • If regulations change frequently • If not all toxins regulated • If detection limit and threshold for action coincide	• Provide certainty • May increase customer trust in DWS			• Experiencing TABs more often	• Experiencing TABs less often
	No regulatory limits for cyanotoxins	• May not identify cyanotoxins even if present	Potentially toxic sludge not regulated	Visual inspections provide unreliable information			
	Regulations that require or recommend analytical techniques for cyanotoxins	• Require non-typical monitoring • Required tests have steep learning curve • Results from required testing are difficult to use for regulatory compliance • Required tests are expensive	• Some DWS reported learning about organism behavior from ongoing monitoring	• If monitoring is not easily incorporated into existing routine monitoring programs • If increased monitoring does not generate better information for TABs management • Required tests are difficult to use, require significant technical expertise, and results are inconsistent or inaccurate • Delays in obtaining results hamper management	• Enable investment in better testing methods and equipment • Monitoring provided helpful information for TABs management	• Monitoring tied to organism behavior • Organism behavior difficult to understand and predict	• DWS use phycocyanin fluorescence as toxin indicator
	No regulatory requirement or recommendation for analytical techniques for cyanotoxins			• Difficult to justify investment in better testing methods and equipment			

in their treatment approach, e.g., using chemicals such as powered activate carbon as a precaution, resulting in unnecessary treatment costs if there is no extracellular toxin present (U8). Needing to determine whether toxin is inside or outside of cells is yet another monitoring process outside the norm of managing typical contaminants and pollutants drinking water.

State regulations often recommend or require that water managers use specific cyanotoxin tests or methods like ELISA, LC–MS/MS, or qPCR (Table 2); yet the complexities in performing tests and obtaining reliable results, as well as the limitations in what cyanotoxins tests can detect, presents a challenge for water managers. For example, the ELISA test is widely used by water managers to test for toxin presence and to estimate how much total microcystins is in the water. However, water managers reported that, *"the Abraxis* [ELISA] *presence/absence field test strips* [for Rapid Contaminant Detection]..." are difficult to use (U1) and results were inconsistent and inaccurate (U11). Even automated cyanotoxin testing systems like the Cyanotoxin Automated Analysis System (CAAS) for ELISA, meant to ease the testing burden, can be challenging to use, requiring steep learning curves (U17). Another challenge with ELISA is that it cannot differentiate between individual toxin variants [60, 83]. For example, one state water manager noted ELISA cannot test for different forms or derivatives of microcystins, and, even if it could, state regulators do not know all the different cyanotoxin forms out there (S6). Finally, test results can be difficult to use for regulatory compliance when cyanotoxin levels are hovering around the minimum detection level. This is because the lower regulatory level limit and detection level for cyanotoxin are the same. For example, the ELISA test has a minimum cyanotoxin detection level of 0.3 μg/L for microcystins, which is the same as the lower total microcystins threshold (0.3 μg/L) for states with cyanotoxin regulations (see Table 1). For water managers this means that ELISA is a useful screening tool for the presence of toxins, but because the detection level (0.3 μg/L) is the same as the health advisory level for young children (under school age), getting a positive results means the water is already a risk for children. One manager stated the challenge succinctly, *"ELISA doesn't give you any warning..."* that cyanotoxins are in the water before it is already a problem (U6). While other methods can quantify toxin amounts (i.e., LC–MS/MS) and screen for the presence of toxin producing genes (i.e., qPCR) [17, 22, 60, 61], both are more expensive and require more technical expertise to perform than ELISA.

Not all DWS required to conduct cyanotoxin testing have the capacity for in-house testing; without in-house testing capacity, these DWS often ship their samples to an outside certified lab resulting in delayed test results. For example, one DWS reported they must ship samples across the country requiring on average seven days for results (U1), which is frustrating in the middle of a crisis (U11). Another manager indicated they experience significant delays, getting their results back "...*maybe a month or more...*" after sample collection (U13*).* The deficiency of accredited labs able to do cyanotoxin testing further exacerbates the problem (S6).

Finally, while most states do not establish limits for cyanotoxins nor require routine monitoring for cyanotoxins, some states do provide guidance to DWS such as recommending visual inspection as a way to determine water source quality (S5; [83]),however, visible blooms (bluish-green, brown, or purple color, surface scum, cloudiness) are an unreliable method of determining the presence or absence of cyanotoxins [18]. Indeed, interview and survey data suggest that water managers, in states without cyanotoxin regulations, often rely on visual inspection to decide whether to test their source water for toxins. For example, a survey respondent said they are trained to recognize possible HABs, and only test for cyanotoxins if a visual bloom is present (SU20). When a bloom is present then they test for toxins using, *"...test kits for microcystin* [and]... *an ELISA plate reader to monitor for toxic algae*" (SU20). Similarly, an interviewee said, "*If we were to see a massive bloom... that might be an indication, we'll do testing* [for cyanotoxins]" (U13). Yet, relying on visual cues could cause toxins to go undetected, putting water customers at risk. For example, one water manager detected toxins during routine monitoring without a visible bloom (U1), acknowledging that visual inspection is not the best approach (U4). This is consistent with Christensen et al. [18] who sampled cyanotoxins before and after a bloom noting the presence or absence of a bloom did not align with the absence or presence of cyanotoxins. With no mandate to monitor, cyanotoxins seep into source water, posing a threat to public health. Table 3 summarizes how interventions in the social dimension (i.e., regulations) increase or decrease TABs management difficulty across social, socio-technical, and socio-ecological dimensions.

Technical dimensions and intersecting socio-technical and socio-ecological dimensions

For conventional treatment plants, having the ability to adjust chemical feed rates (e.g., powdered activated carbon (PAC), chlorine, chloramine, chlorine dioxide) and/or flow rates through the water treatment plant, gives water managers flexibility to treat cyanotoxins. This flexibility, however, has limits and can also create other problems. For example, some managers increase chlorine contact time from 7 or 8 h a day, to 13 or 14 h a day in hopes of reducing toxicity (U8). While increasing chlorine contact time allows the chlorine to oxidize cyanotoxins (Merel et al. 2020), not all cyanotoxins respond in the same way. Increasing chlorine dosing and contact time is effective at reducing toxicity of microcystin and cylindrospermopsin but not anatoxin-a, due to its slow reaction kinetics [53]. Chorine is also ineffective if the toxin is intracellular, as "*…whole cells … protect [the toxin] from chlorine by being still enclosed by the cell wall*" (U3). Adding too much chlorine or increasing contact time too long can cause other problems, in particular increasing disinfection byproduct (DBP) formation, which in turn, may put water managers at risk of violating DBP limits established under the Safe Drinking Water Act. One water manager noted that, "*… because I keep a free chlorine residual so high… I form a lot of disinfection byproducts in my system… it puts me over* [the limit for] *disinfection byproducts…* (U15). Thus, water managers must manage algal blooms, while trying to prevent DBP formation (SU22). Table 4 summarizes interventions in the technical dimension (e.g., process flexibility, new treatment processes) that can increase or decrease TABs management difficulty across technical, techno-social, and techno-ecological dimensions.

For most DWS, treatment plants offer limited or no flexibility. For example, complete toxin removal using PAC that adsorbs extracellular toxin often requires high PAC dosing amounts (i.e., more than 20 mg/L) [76]. However, PAC is expensive and not all DWS can afford to dose at high levels for extended periods of time (U11), nor can some water systems handle high PAC dosing for extended periods (U11,SU23). Others have no flexibility to adjust their chemical feeds or plant flow rates. Two water managers interviewed indicated that, "*…chlorine contact time is* [fixed and is] *only 20 min,*" so, if toxin concentrations are too high, there is not much they can do to reduce toxin amounts using the treatment plant (U2; SU21).

Water managers equipped to identify the type of cyanobacteria and whether the toxin is intra- or extra-cellular can make more informed treatment decisions (e.g., to lyse cells and treat the extra-cellular toxin or leave the cells intact and remove them via filtration); nevertheless, each option comes with limitations and challenges. Purposeful lysing works well for *Microcystis* because these cyanobacteria lyse easily with permanganate (U4), allowing water managers to treat the extra-cellular toxin if they have the capability to add PAC and chlorine and so long as they manage DBP formation. Other cyanobacteria like *Planktothrix*, which has a "*hardy cell wall*", do not lyse easily and are often removed whole as explained by this water manager, "*…*[*Planktothrix*]*… is easier to remove the whole cell and with it the cyanotoxin concern*" (U4). For this particular DWS shifting treatment to remove whole cells required upgrading clarifiers at considerable cost from what were traditional gravity settling clarifiers to new dissolved air flotation units capable of removing floating *Planktothrix*.

Removing whole cyanobacteria creates other potential challenges both within the plant and with sludge handling and disposal. First, intact cells may produce toxins within the treatment plant, particularly in the sludge beds and clarifiers as noted by this water manager, "*…there's been a few studies now that show you can have growth within sludge beds. You can have growth within your clarifiers. So, you can be producing the toxins within your plant…*" (U1). The potential for producing cyanotoxins within a plant complicates treatment. Second, if cyanobacteria are kept whole, then the sludge produced by the treatment process is assumed to be toxic and, as such, requires a different, more costly management approach. The potential for producing cyanotoxin contaminated sludge has reshaped how water managers deal with sludge, as noted by this water manager, "*Most of our sludge is actually lime sludge. So, we were putting it on farmland,*" but after experiencing TABs, "*… it was recommended that… the sludge be tested for microcystin if we see it in our raw* [water]" (U15). Now, "*… We totally removed it from farmland and went right to landfill with all our sludge*" (U15). Another water system producing sludge with, "*…a lot of lime and cyanobacteria solids… won't be able to lagoon them like we do now,*" but instead will, "*…thicken the solids to about 15% water… mix that with fuel and burn it to get rid of the cyanotoxin contaminated solids. It won't be cost neutral but it will solve the problem*" (U4). Of course, in states without cyanotoxin regulations, the potential for toxin contaminated sludge is not a consideration.

Social dimensions that challenge water managers

Water managers who encounter cyanotoxins, or risk detecting them in their drinking water, struggle to communicate with water customers about cyanotoxin risks because risks vary depending on the population exposed and because decisions to limit risk can erode public trust in drinking water. One water manager captured the communication challenge noting the different regulatory limits for different age groups "*…is hard to explain to the public*" (U10). Another manager expressed their frustration saying, "*How do you say* [to the public that] *it is not okay for a 6-year-old to drink the water, but a 6.5 year old or a 7 year old…is fine?*" (U3). Even more complicated for water managers is issuing a 'Do not Drink' or 'Do not Consume' advisory if cyanotoxins are detected in the treated water. Water managers explain that such declarations can erode public trust in drinking water supplies:

Table 4 Interventions in the technical dimension (e.g., process flexibility, new treatment processes) that can increase or decrease TABs management difficulty across technical, techno-social, and techno-ecological dimensions

	Interventions	Social Dimensions		Technical Dimensions		Ecological Dimensions	
		Management Difficulty		Management Difficulty		Management Difficulty	
		Increased	Decreased	Increased	Decreased	Increased	Decreased
Technical Dimensions	Process flexibility at the treatment plant	• Excess DBPs cause SDWA violation • Chemical dosing is expensive (e.g., PAC)		• No ability to adjust chemical feed or flow rates • Increased chemical dosing causes DBPs • Must treat incoming toxins and toxins that form in the WTP	• Ability to adjust chemical feed or flow rates • If able to identify type of toxin and whether cells are intact or not, may proactively lyse cells with permanganate and treat with PAC and chlorine or filter whole cells with new technology	• Slow reaction kinetics of anatoxin-a make dosing less effective • Intact cells may produce toxins within the plant	• Microcystin and cylindrospermopsin reduced with greater chlorine exposure
	New treatment processes	• New treatment processes are expensive		• Toxic sludge adds potential for new treatment needs	• New treatment technology capable of removing toxic algae	• Some toxic algae float (Planktothrix)	
	New waste streams generated	• Toxic sludge adds disposal and monitoring costs and new sludge handling protocols		• TAB contaminated sludge is considered toxic		• Intact cells may produce toxins within the sludge	

"... if we see cyanotoxins... in finished water it's a 'Do Not Consume', which is a huge issue for a utility. ... in terms of the logistics ... But also, in terms of consumer confidence in the utility. Which is a really long-lasting impact..." (U1).

This became a reality for a water system that issued a 'Do Not Drink' advisory as recommended by their state regulator after finding cyanotoxins in their finished (i.e., fully treated) drinking water. Referring to this event, a water manager at a nearby water system noted that although the utility, *"... did the right thing and reported what they found with the toxins... they received some really bad press because of it" (U11).* Another water manager nearby said that the cyanotoxin violation by their neighbor utility decreased customers' trust in their water despite not having any cyanotoxin violations themselves (U3). To help build public trust, this water manager proactively met with their water customers to help them better understand the risks and safety of their water supply:

"We try to communicate with our customers as often as we can. ... If someone calls us up with an issue with their water or how it tastes, we go to their house. We put a face to the organization. It helps to build trust" (U3).

In addition to better communication around an event, some water managers increase overall transparency to proactively build public trust. For example, one water system noted their toxin levels in raw and finished waters is available on the state regulator's website for the public to see (U4). Another manager said that they disclose warnings and toxin levels in their Consumer Confidence Report, and regularly update their website with information on drinking water quality (U11). Both water managers suggested that being more transparent with toxin data lets the public know that they are not hiding anything. Despite these approaches, our results suggest communication can both help and hinder TABs management difficulty (see Table 5).

Discussion

While TABs management challenges encompass multiple dimensions, research tends to focus on a single dimension at a time ignoring important intersections and potentially missing important insights. For example, research focusing on technical dimensions finds chlorine is effective at oxidizing some but not all cyanotoxins (Merel et al. 2020). But this insight alone is not enough to help DWS seeking to manage TABs. This is partly because DWS managers must first identify which algal toxins are in the source water (and whether the toxin is intra- or extra-cellular) and if the particular algal toxin is amenable to oxidation (T-E dimensions). If the toxin can be oxidized (T-E dimension), and if the treatment plant can accommodate additional dosing or contact time (T dimension), then DWS managers may employ this strategy. However, from interviewees using this strategy, we learned that increased chemical dosing can cause other problems such as increasing other contaminants (e.g., DBPs) [84] that risk SDWA violations and raise treatment costs (S-T dimension). We also learned that not all DWS managers have the capacity to identify specific algal toxins (S-T dimension). This suggests that purely technical information and solutions when applied in a real-world context, are insufficient because ecological stressors (cyanotoxins) interact with socio-technical systems in dynamic ways (i.e., DWS managers use technology to identify and treat cyanotoxins (e.g., using high levels of oxidizers like chlorine) to protect public health but create carcinogens (e.g., disinfection by products at too high amounts harmful to public health and violate drinking water regulations).

Similarly, other technical-focused research suggests most existing drinking water infrastructure cannot completely remove algal toxins [9, 38, 85, 86]. While this is an important insight, conversations with DWS managers helped to disentangle how treatment challenges manifest in practice and how they intersect with SETS. For example, whether the cyanotoxin is intra- or extracellular and the type of cyanobacteria matters, though not all DWS managers have the capacity to determine

Table 5 Interventions in the social dimension (e.g., communication) that can increase or decrease TABs management difficulty

	Interventions	Social Dimensions	
		Management Difficulty	
		Increased	**Decreased**
Social Dimensions	Communicating about cyanotoxins	• Communicating about risks that vary depending on the population at risk • Issuing do not drink advisories erode public trust	• Proactively meet with water customers to explain risks • Proactively disclose toxin levels and warnings

specifics about their TABs to inform treatment (T-S dimension). With intracellular toxins, we learned that treatment processes that leave cells whole can be effective initially; however, complications arise when intact cyanobacteria produce toxins inside the plant as well as when dealing with sludge contaminated with cyanotoxins (E-T dimensions). Indeed, research shows that partially oxidized cells retained on a filter surface or in solids can continue to release toxins into the finished drinking water [34] or worse, break through filter media and end up in the finished water [88]. Dealing with these complications requires additional testing (for toxins within the plant not just in the source water and for testing sludge for toxin contamination) and disposal costs (for toxic sludge) (T-S dimensions) and potentially expensive new treatment processes to remove toxic algae. Interviewees noted the added monitoring costs as well as chemical and waste disposal costs associated with cyanotoxin treatment are not insignificant and can quickly eat up annual operating budgets. These costs are often passed onto consumers in the form of increased drinking water costs. A recent report documented rising costs of drinking water in Toledo resulting from increased monitoring with households paying nearly $100 more per year for drinking water [1]. Again, this example shows how ecological stressors (cyanotoxins) interact with technology and socio-technical systems creating cascading impacts. Approaching the problem from a more holistic SETS lens helps to illuminate these interconnected SETS issues that scholars and drinking water practitioners may otherwise overlook if focusing only on one dimension or considering only STS or SES.

Just as technical dimensions focused research is insufficient, social dimensions focused research too provides an incomplete picture of the range of challenges managers face. For example, Treuer et al. [75] concluded that the lack of federal regulations increases management difficulty by leaving DWS managers unprepared if TABs occur,yet, our in-depth study revealed regulations both increase and decrease TABs management difficulty. Using a SETS lens, we find that regulations can help ease management difficulty by providing certainty and helping to justify investments in new technologies and equipment to improve management. Regulations can also ease customer concerns about the quality of drinking water both of which are social dimensions issues. However, we found regulations also increase management difficulty particularly while DWS managers and state regulators learn and adjust. Management difficulty is also increased because regulations requiring monitoring are challenging to implement as TABs monitoring is not easily integrated into ongoing monitoring programs. Established monitoring programs are akin to sociotechnical structures, resilient until they become destabilized [70]. In this case, the destabilization comes from the ecological dimension. Unlike conventional contaminants and pollutants that are well characterized by routine monitoring, cyanotoxins require non-standard monitoring approaches and organism behavior is difficult to predict [60, 83]. Consistent with He et al. (2016), cyanotoxin tests are difficult to use, and results are sometimes difficult to interpret, further challenging efforts to establish new sociotechnical structures for monitoring. These two challenges might help explain our finding why new monitoring requirements did not lead seamlessly to improved TABs decision making. Dealing with unfamiliar ecology and unfamiliar technology makes it doubly hard for water managers to find their footing in the SET system. Finally, communicating cyanotoxin risks to the public is challenging for water managers given the complexities of the contaminant and what we know about who is at risk and when. Thus, regulations, in some cases, may actually increase TABs management difficulty, largely because of interacting SETS factors that undermine the DWS managers' ability to make informed TABs management decisions.

While not having regulations is associated with fewer TABs management challenges, interviewees indicated that states often advise DWS managers to rely on visual inspection of source water quality to decide whether to test for toxins (also noted in Yeager & Carpenter [83]). Yet, visible blooms are an unreliable indicator of the presence or absence of cyanotoxins [18] and reliance on visual inspection may mean cyanotoxins go undetected putting public health at risk. Likewise, if DWS managers do not perceive cyanotoxins to be a problem for their system, toxins may go undetected putting public health at risk [51, 71, 75]. Moreover, toxic algae may contaminate sludge, and for states without cyanotoxin regulations, contaminated sludge may be unknowingly spread onto farmland or other land areas used for sludge application and disposal.

Conclusions

In this paper we investigate TABs and their management as an example of a complex EC problem through the lens of interconnected social, technological, and ecological systems (SETS). We use mixed methods including new analysis of a national survey of public drinking water systems and interviews with drinking water managers and state regulators to advance a holistic understanding of TABs management in drinking water systems, extend SETS to the drinking water context, and identify specific intervention points to ease TABs management difficulty. We aimed to uses insights from our investigation of TABs to inform broader considerations of ECs management.

We build on prior research that found TABs are difficult for water managers to deal with and offer a more nuanced view of what makes TABs harder or more difficult to manage. Our analysis suggests that rather than making TABs management easier as we might intuit, cyanotoxin regulations (S dimension) can increase management difficulty. Challenges arise at the intersection of SET domains, as unfamiliar ecology intersects with new testing methods and protocols, established treatment approaches, and spawns communication challenges. Challenges arise with testing in part because traditional routine monitoring does not work for cyanobacteria. Rather, testing occurs more frequently than routine testing is typically performed, is more difficult to do, and test results may not be automatically helpful (intersecting SETS domains). Treatment is also challenging. Treatment challenges stem in part from the need to adapt existing infrastructure—designed to remove conventional pollutants and contaminants—to remove unconventional biological toxins. For some water systems, treatment systems are less flexible making it more difficult to increase chemical dosing amounts or to add or change chemicals used in the treatment process. And, for some systems, adjusting treatment processes to remove toxins or cells can cause other problems (e.g., forming regulated carcinogens in drinking water, toxin production within the treatment process, toxic sludge). Treatment challenges like these increase TABs management difficulty. Finally, complex ecologies intersect with regulations and testing limitations confounding communication with the public about who is at risk and when.

TABs management is made easier, when there are fewer intersecting SET domain issues. For example, in states where cyanotoxin regulations provide certainty, water managers invest in treatment and testing (S-T domain). In turn, when such investments are themselves not difficult to manage (i.e., treatment and testing are doable) (S-T domain), testing produces good information for decision-making (S-T domain) and treatment results in good quality drinking water (E-T domain), making TABs management easier. Finally, good outcomes and open and transparent communication with the public, improve public trust of drinking water (S domain), making TABs management easier.

While not having regulations is associated with fewer TABs management challenges, our research suggests that toxins may go undetected putting public health at risk [51, 71, 75]. Moreover, toxic algae may contaminate sludge, which may be unknowingly spread onto farmland or other land areas used for sludge application and disposal spreading toxins far from source waters. In areas where TABs are emerging or increasing, new regulations protective of public health may be a prudent step if there are also provisions for financial assistance to water systems to make investments needed to comply with those regulations and provided these investments help moderate drinking water rate increases to avoid undue financial burden on residents. Absent new regulations, increasing surveillance for cyanotoxins in drinking water sources could help identify where toxins are of greatest concern enabling targeted next steps.

Prior research on ECs and TABs in particular mostly focus on a single dimension, often technical and this oversimplifies both ECs as a problem and the effectiveness of potential solutions. We identify a range of intersecting SET factors associated with TABs difficulty. We find that management challenges arise at the intersection of SET domains, and often coincide with circumstances where water managers and technologies are pushed outside of their traditional operating spheres. Understanding how management difficulties arise within SET domains and their intersections may help DWS and state regulators mitigate management difficulties in the future by thinking more holistically about their response. For example, facilitating learning around monitoring and regulatory compliance when issuing new regulations or modifying existing regulations would help lower SETS challenges. This kind of training is regularly provided when the USEPA issues new regulations, such as those for PFAS. But states may need more assistance in providing effective training programs particularly when managing for ECs that may not behave like conventional pollutants and contaminants and when monitoring and testing are also new and different. Leaning into evidence-based approaches like peer-to-peer learning can help as well as sharing both challenges and successes can aid DWS managers improve TABs and ECs response more broadly.

Future research is needed that applies SETS to other emerging contaminants to understand ECs and their management more holistically and to explore whether and how intersecting SETS increase (or diminish) management challenges. Within TABs research, interventions aimed at reducing SET domain issues such as improving TABs prediction (T domain) and testing tools (T domain) or providing training to improve communicating TABs risks with water customers (S domains) or reducing intersecting SET issues (e.g., training for testing coupled with better tests) could be assessed for their effect on reducing TABs difficulty.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Authors' contributions
C.K. and C.M. wrote the main manuscript text. C.K. and R.D. conducted interviews and analyzed interview data. C.K., M.C.L., G.T conducted the survey and C.M. analyzed the survey data used in this manuscript. C.K. prepared Fig. 1 and tables. All authors reviewed the manuscript.

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Data availability
De-identified data is available upon request.

Declarations

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