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Employing a socio-ecological systems approach to engage harmful algal bloom stakeholders

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Abstract

Harmful algal blooms (HABs) pose substantial health risks to seafood consumers, drinking water supplies, and recreationalists with apparent increases associated with anthropogenic eutrophication of freshwaters and coastal areas. Attempts to intervene in these blooms can be met with reticence by citizens, non-governmental organizations, and officials, often due to local perceptions and beliefs. Hence, the social sciences have an important role to play in HAB research and mitigation. Much of the social science HAB research to date has focused on how best to communicate associated risks and appropriate behavioral responses to affected local communities. The emphasis has been on the direct human impacts, particularly in the areas of health outcomes and identification of any sociocultural and economic barriers to proposed mitigation. While this focus is warranted and valuable, there is also a need to understand HABs as part of a larger human–environmental coupled system, where blooms trigger a wide range of cultural and behavioral responses that are driven by how blooms impact other social and ecosystem dynamics. The research presented here describes a case study of a *Microcystis aeruginosa* bloom in a lake in the Chesapeake Bay watershed where anthropologists worked with HAB researchers. The results of this interdisciplinary collaboration show that approaching the bloom and mitigation within a ‘socio-ecological systems’ framework provides stakeholders with a range of rationales and

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Compliance with ethical standards

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approaches for addressing HAB mitigation, enhancing both short-term successes and longer-term opportunities, even if *M. aeruginosa* is still present in the lake.

Keywords

Socio-ecological systems; Stakeholder response; Mitigation; Microcystis aeruginosa

Introduction

Harmful algal blooms (HABs) are a significant environmental problem that is increasingly impacting human–environmental coupled systems as a result of global expansion of nutrient enrichment and warming water temperatures (O'Neil et al. 2012; Heisler et al. 2008; Paerl and Huisman 2008). These events have a direct impact on the health of key aquatic and marine species through the production of toxins and alterations to important ecosystem function and food web dynamics (Landsberg 2002), potentially resulting in large-scale morbidity and mortality events (e.g., Pitcher et al. 2014; Harding et al. 2009). Toxin exposure also poses significant health vulnerabilities to human populations through ingestion or skin contact (Fleming et al. 2002). Additionally, HABs threaten vital socioeconomic infrastructure through closure of important recreational areas and fishing grounds that sustain commercial and tourism industries, and other important cultural resources. Impacts on economic drivers, livelihoods, and cultural amenities (Hoagland et al. 2002; Lipton 1999) have potentially long-term consequences for coastal community well being. As a result, there is increasing need for management tools to better assist communities in responding to HABs.

While research to date has recognized the ecological and human dimensions of HABs, much of the human dimensions research has focused primarily on causes and health impacts (e.g., Bauer 2006). Though warranted and valuable, this research needs to encompass a broader spectrum of the social dynamics relevant to HAB prevention, control, and mitigation. This is particularly important as expanding impacts of HABs will increase the frequency and types of human response. Research that develops understandings about the drivers affecting human and ecosystem dynamics will better equip research and management communities in developing robust solutions to HAB perturbations.

As environmental anthropologists and other social scientists engage in HAB research (Van Dolah et al. 2014; Paolisso and Chambers 2001; Paolisso and Maloney 2000; Paolisso 1999), often as parts of interdisciplinary teams, a conceptual framework is needed that integrates methods and contributions of both the ecological and social sciences. Using a case study on Williston Lake, a small lake draining into a tributary of the Chesapeake Bay in eastern Maryland, USA, this paper argues that a socio-ecological systems (SES) approach is a useful orientation for meeting these needs. In 2010–2011, Williston Lake was impacted by recurrent cyanobacterium blooms of *Microsystis aeruginosa* that produced ecological, health, and socioeconomic challenges to a variety of local and regional stakeholders. Through social and ecosystem science research, we identified and worked with key stakeholders and decision-makers affecting the lake's response to the blooms. We also

identified key ecological and physical conditions of the cyanobacterium and lake that support successful intervention. Our results reveal the emergence of three primary factors affecting human response to HABs: lake access, nutrient management, and broader Chesapeake Bay restoration efforts. From the ecological research, the study supports the routine use of hydraulic flushing and inexpensive deployment of barley straw, *Hordeum vulgare,* prior to bloom development as practical approaches to limiting accumulations of the toxic cyanobacterium in freshwater systems.

Conceptualizing HABs within social-ecological systems

Socio-ecological system (SES) research is a comprehensive social and ecosystem sciences approach to study the complex, nonlinear interactions between social, cultural, political, ecological, and biophysical processes. SES research recognizes that human and environmental dynamics are entangled in ways that make it problematic to study each in isolation. It provides a theoretical lens for understanding how human and environmental dynamics feed back into each other across multiple temporal and spatial scales (Berkes and Ross 2013; Walker and Salt 2006; Lambin 2005). In doing so, it accounts for not only the ways that humans affect ecological and biophysical structures and function, but also how ecosystems dynamics shape environmental values, perceptions, behaviors, and practices, as well as broader social organization and governance. Expanding on traditional ecosystem theories of resilience, vulnerability, and complex adaptation, SES research seeks to explain how these coupled systems develop, respond, and adapt to emergent environmental perturbations (Gunderson 2003; Gunderson and Holling 2002; Holling 1986). HABs, as examples of such perturbations, emerge in the context of these complex human–environmental interactions.

We propose an SES framework (Fig. 1) that is useful for an interdisciplinary study of HABs. The framework approaches HABs as events that prompt a range of human and ecosystem responses that affect how the overall system responds to HAB perturbations. Human responses are embedded within political dynamics (e.g., nutrient regulation, environmental health policies), economic dynamics (e.g., property values, income), and cultural dynamics (e.g., aesthetics and place-based values) that trigger individuals to react in socially contextualized ways to the onset of a bloom. Human responses are spatially diverse (e.g., local land use change or distant government directives) and temporally distributed (e.g., immediate intervention vs. delayed legal decision) (Cote and Nightengale 2012; Gunderson and Holling 2002). Individuals can also be heavily influenced by past experiences, knowledge, and relationships to ecosystem services (Paavola and Hubacek 2013; Collins et al. 2010; Ostrom 2009) as well as their connectivity to social networks (Berkes and Ross 2013; Bodin and Crona 2009). For example, individuals engaged in regional environmental management programs may respond differently from those who are part of a community of recreational end-users as a result of who and what they know and value. Likewise, individuals with past experience and associations with HABs will apply those experiences to direct their response to new HAB encounters.

In contrast, ecosystems respond to HABs through changes to key ecosystem processes and characteristics such as water quality, dissolved oxygen (DO), light penetration, fish kills, and

altered food webs. These are visible as changes to benthic [e.g., loss of submersed grasses and hard clams (Gastrich and Wazniak 2002], deep water anoxia-dead zones [Heisler et al. 2008)], and pelagic community populations and composition [e.g., lower copepod fecundity (e.g., Dam and Colin 2005), allelopathic exclusion of HAB competitors (Granéli and Hansen 2006), secondary fish infections [e.g., Kiryu et al. 2002)]. Ecosystem response to HABs is also temporally and spatially varied, occurring in rapid bursts with cumulative changes that are nested in local– global dynamics (Li et al. 2015; Collins et al. 2010; Zurlini et al. 2006).

Ecosystem and human response to HABs do not occur in isolation. Ecosystem changes prompt humans to react in particular ways (e.g., water discoloration leads to reduced recreational activity), just as human intervention triggers ecosystems to adjust to associated anthropogenic activities (e.g., mitigation reduces plankton cell counts). The feedbacks between human responses and ecosystem changes determine whether the overall system recovers from the impacts of a HAB. If poorly understood and managed, these responses can have immediate and long-term unexpected consequences, resulting in increased ecological variability that adversely impacts social organization and practices, thus causing the SES to shift to a potentially deleterious state. Applying a SES orientation to HAB research and management can illuminate the underlying drivers—factors that trigger particular responses or changes—and highlight challenges and opportunities for aligning human and ecosystem processes more effectively through directed interventions.

Chesapeake Bay HABs

Blooms of *M. aeruginosa* are common to many parts of the Chesapeake Bay watershed, as are large blooms of several other eukaryotes, mostly dinoflagellates, raphidophytes, and macroalgae. In general, these blooms have been largely addressed through reactive responses from researchers and managers without dialog with citizens, commercial fishers, advocacy organizations, or others. *M. aeruginosa* blooms have been documented in the Potomac River (Fig. 2a), estuary, and its tributaries [including Mattawoman Creek (Fig. 2b) discussed below] for more than 40 years (Jaworski et al. 1972). More recent *M. aeruginosa* blooms have been observed in the tidal fresh Sassafras (Fig. 2c) and James Rivers (Fig. 2d) (Li et al. 2015; Gao et al. 2014; Bukaveckas et al. 2011) as well as many lakes and ponds throughout the region (Sellner et al. 2015).

Dinoflagellate blooms are also quite frequent. Since 1978, *Prorocentrum minimum* has typified phytoplankton blooms in the late spring of the Chesapeake Bay (Li et al. 2015; Tyler and Seliger 1978). One strain has been found to reduce juvenile oyster growth (Luckenbach et al. 1993), which is worrisome for a continuing effort to restore native oysters and a fledgling aquaculture industry. Additionally, *P. minimum* biomass accumulates to high levels and has been associated with low dissolved oxygen (DO) and fish kills (Brownlee et al. 2005). The ichthyotoxic *Karlodinium veneficum* is also common, likely responsible for the fish mortalities attributed to *Pfiesteria piscicida* in the late 1990s in Maryland tributaries (Fig. 2e, f) to the Chesapeake Bay (Place et al. 2008) (see below). *P. piscicida*'s reported human health threats were responsible for severe economic losses approximating $43M (US) to local seafood industries, affecting fishers, charter boats, restaurants, grocery stores, etc. (Lipton 1999). *K. veneficum* continues to flourish aperiodically with associated fish kills

(Li et al. 2015; Goshorn et al. 2004). Other dinoflagellates pose threats to the lower Chesapeake Bay and major tributaries like the James (Fig. 2d) and York Rivers (Fig. 2g). Blooms of the cystforming *Alexandrium monilatum* are now fairly common in the lower York River estuary, producing a toxin lethal to whelk, cow rays, oyster larvae, and laboratory fish (Harding et al. 2009; Vogelbein et al. 2015) and posing perceived threats to shellfish consumers. *Cochlodinium polykrikoides* reaches bloom levels in the lower James River estuary (Mulholland et al. 2009). As a known fish killer and recently identified in mortalities of laboratory oyster and fish larvae (Reece et al. 2015), *C. polykrikoides* also causes some alarm for local fishers, recreational users, and management communities. *Dinophysis acuminata* was responsible for oyster harvest closures in the lower Potomac River estuary in 2002 (Tango et al. 2004) and is a frequent member of the phytoplankton community in coastal lagoons in eastern Maryland (Glibert et al. 2007). Diarrhetic shellfish poisoning (DSP) from the *D. acuminata* introduction of this taxon may become more common in the Chesapeake Bay as a result of more frequent, large coastal ocean intrusions from extended droughts induced by climate change (Najjar et al. 2010). Raphidophyte blooms (*Chattonella*, *Heterosigma*, *Fibrocapsa*; Fig. 2j) are also common to eastern Maryland lagoons (Maryland Department of Natural Resources 2015), as well as the brown tide organism *Aureococcus anophagefferens* (Fig. 2k, l) (Glibert et al. 2001), though on a less frequent basis. Blooms of macroalgae (*Gracillaria*, *Codium*; Fig. 2i, k) also typified these systems in the 1990s–2000s (e.g., Wazniak et al. 2007; Thomsen et al. 2006), leading to suffocation of submersed grasses, low DO, foul smell, and aesthetically unappealing shorelines. Most of these HABs result in short-term public official responses (e.g., announcements, news articles, occasional advisories/closures). While some local citizens voice concerns about HABs, there is currently little citizen-industry-manager-scientist dialog on acceptable interventions.

Two Chesapeake Bay HAB events illustrate the importance of approaching HABs within an SES framework. As previously noted, several estuaries in the lower Chesapeake Bay (Fig. 2e, f) experienced isolated fish kill events initially linked to the dinoflagellate *P. piscicida.* Co-occurrence of the ichthyotoxic *K. veneficum* at cell densities nearly 100-fold higher than *P. piscicida* raised questions among the scientific community about the role of *P. piscicida* in these fish kills (Place et al. 2008). Extensive media coverage of *P. piscicida*, however, resulted in large-scale public reaction, touted the ‘pfiesteria hysteria,’ that overemphasized and misinterpreted the associated health risks due to misaligned cultural orientations and beliefs (Kempton and Falk 2000; Paolisso and Chambers 2001). The event had immediate impacts on the socioeconomic health of seafood industries (Lipton 1999), and long-term impacts on the agricultural community, which was blamed for the excess nutrients that prompted the harmful algae event (Paolisso and Maloney 2000). Public reactions in part influenced environmental decision-makers to implement more stringent regulations that the farming community believed (and still believes) unfairly punished them as polluters (Paolisso and Maloney 2000).

In a second case study, lack of SES considerations resulted in failed management planning. As noted above, *M. aeruginosa* blooms have been regularly observed in Mattawoman Creek (Fig. 2b) in the tidal fresh portion of the Potomac River estuary for more than four decades, largely due to elevated nitrogen and phosphorus from the largest wastewater treatment plant (Blue Plains Advanced Wastewater Treatment Plant, serving Washington, D.C.) in the

Chesapeake Bay watershed. In response to bloom effects on the creek ecosystem, the Maryland state government recommended a development plan in 2011 to curtail nutrient input, thereby reducing the occurrence of the HABs and restoring the ecological health of the creek. However, local citizen groups and local government officials rejected the plan because it failed to account for key cultural factors (e.g., environmental and recreational values) and socioeconomic factors (e.g., desires to invest in Smart Growth development within the Mattawoman Creek watershed) valued by the community (Van Dolah et al. 2014). Limited considerations of the human dimensions of Mattawoman Creek led the local government to not implement State recommendations, thereby leaving Mattawoman Creek more vulnerable to future HABs.

Methods

Study site description

Williston Lake is a 26-ha dammed lake near the city of Denton in Caroline County, Maryland, USA (38°49′51.2″N, 75°50′26.92″W, Figs. 2, 3). It is located at the headwaters of the Choptank River (Fig. 2h), one of the major tributaries of the Chesapeake Bay. The lake drains largely agricultural cropland, principally corn and soybean, fertilized with synthetic fertilizers and poultry litter. The surrounding landscape has been in continuous crop production (R. Foote, pers. communication). As a result, soils are phosphorus-enriched (in some areas phosphorus-saturated) and surface and groundwaters are typified by nitrate-nitrogen concentrations approximating 15 mg L^{1} (Knee and Jordan 2013; Sanford and Pope 2013; Staver and Brinsfield 1998; Bachman and Phillips 1996). There are residential septic fields directly upstream and surrounding the lake (Fig. 3), though their nutrient input is unknown.

The lake is privately owned by the Girl Scout Council of the Chesapeake Bay (Girl Scouts), which inherited the property in 1958 to establish Camp Todd (A.T. Hogan, pers. communication). The Girl Scouts share lake access with nineteen lakefront residential landowners. The camp and landowners primarily use the lake for recreational purposes, including bass fishing, canoeing, and swimming. Access outside of the lakefront community is restricted to a scenic overlook adjacent to the local highway that passes by the lake at the dam. Most of the lakefront properties are not actively farmed, though interviews with key informants suggest that much of the land was once cultivated.

In 2009, Williston Lake experienced its first cyanobacterium bloom with repeated blooms in 2010–2011, dominated by *M. aeruginosa*; cell abundance exceeded 10^6 mL^{-1} and microcystin concentrations approximated 80 ppb (Sellner et al. 2015), well over the World Health Organization's 10 μg L^{-1} recreational use threshold (World Health Organization 2015). This resulted in a Maryland state advisory for recreational non-use in 2010 and 2011, severely curtailing the Girl Scouts' and landowners' lake access.

HAB management approaches focused on implementing short-term mitigation strategies to reduce blooms and restore lake usage. A range of mitigation strategies was considered, including shortening *M. aeruginosa* residence times in the lake through the manually controlled dam; increasing nutrient- and sediment-trapping wetland areas between the creeks

and the lake to limit nutrient supplies for cyanobacterial growth; adding phosphorus-binding reagents to reduce phosphorus availability for cyanobacteria (PhosLock®, Robb et al. 2003); introducing cyanobacteria-inhibiting barley straw found effective in a local farm pond and for many but not all taxa in other systems (see Brownlee et al. 2003, Spencer and Lembi 2007); and draining the lake during the winter to expose settled vegetative *M. aeruginosa* populations to cell-disruption from intercellular ice crystal formation, thereby reducing stocks of the cyanobacterium for spring resuspension and summer growth. The two latter approaches were implemented by the Girl Scouts starting in the fall 2011 and continued to the present.

Social science methods

Social science data were collected at Williston Lake using ethnographic methods (Schensul et al. 2015), including participant observation (Musante 2015), semi-structured interviews (Quinn 2005; Wengraf 2001), and text analysis (Wutich et al. 2015). Participant observations were conducted at two community meetings. Stakeholder groups and key informants were identified at meetings as well as through snowball sampling, an informant-directed sampling approach for accessing hard-to-reach populations (Bernard 2013). Following these meetings, 27 semi-structured interviews were conducted with key informants from each of the identified stakeholder groups (see below). Interviews were guided by ten semi-structured questions used to elicit knowledge about HABs and mitigation. Key informants were asked the same set of questions, thus ensuring comparability across responses. Each interview was recorded and then transcribed and analyzed using a coding process in Atlas.ti© text analysis software to identify core themes and sub-themes (Wutich et al. 2015). The text analysis was completed in three stages. First, text was coded [i.e., highlighted and tagged with a categorical descriptor (e.g., 'environmental values')] to identify an initial list of themes. This list included four primary themes: drivers of stakeholder engagement; constraints to mitigation; perceived benefits or opportunities; and preferred solutions. These themes guided the second stage of analysis whereby the same interviews were again coded to identify sub-themes that defined specific drivers, constraints, opportunities, and preferred solutions for each stakeholder group. Results were used to assess areas of agreement and disagreement between stakeholders, and identify broader cultural, political, socioeconomic, and ecological dimensions affecting stakeholder response.

Ecosystem science methods

Mitigation in the lake focused on rapidly draining the lake in late fall to one-third of its volume, with bottom shear stress important in resuspension of the overwintering *M. aeruginosa* populations and advection downstream (Sellner et al. 2015). The exposed bottom and any remaining surface or interstitial *M. aeruginosa* would also be subjected to winter's freezing temperatures, potentially leading to ice crystal formation within cells and population lysis. In the following spring, 500 bales of barley straw, *Hordeum vulgare*, were secured across the lake and incoming streams, and left exposed to sunlight for several months for decomposition and production of inhibitory compounds. Chlorophyll *a* and phycocyanin were monitored with a Turner Designs Aquafluor® florometer as well as an in water sensor system (YSI 6920 Ve-2 Multi-Parameter Water Quality Sonde); the latter also measured pH and DO. Grab samples were collected and composition determined via light

microscopy on live and fixed (acid Lugol's solution) samples. Toxin concentrations were also determined on grab samples using a microcystin ELISA (Abraxis Microcystin-DM Elisa) as well as deployed SPATT HP20 resins subsequently extracted with solvent and passed through a LC–MS or analyzed by ELISA (Mackenzie et al. 2004).

Results

Social science research: stakeholder groups

In assessing the human dimensions of the Williston Lake HABs, we found it useful to focus on key stakeholder groups: the Girl Scouts, lakefront landowners, farmers, environmental professionals, and scientists. Each represented diverse interests, needs, knowledge, and values about the lake and HABs, and a range of responses informed by different political, socioeconomic, and cultural factors. Below is a summary of ethnographic data collected on each stakeholder group. Verbatim quotes from the interviews are used to illustrate key informant findings and to provide ethnographic grounding to better understand the SES.

Girl Scouts

When Caroline County environmental health officials posted advisories and closed the lake for recreational use in 2010–2011, the Girl Scouts sought assistance in addressing the blooms from the state of Maryland's Department of Natural Resources (MDDNR). The *M. aeruginosa* blooms coincided with high-season camp attendance, and as a result, there were concerns that lake closure would severely affect the experience of campers and the long-term sustainability of Camp Todd. As reported by a camp ranger, the lake is a vital part of camp experience:

> The lake is one of the things that makes that camp…. It's really special to be right on that lake, and they [the girl scouts] can swim, they can boat, they have the island with the towrope ferry, and one of my favorite things is sleeping in one of those Adirondacks [huts] that overlooks the lake. The girls love to go out and look at the turtles that lay on the logs, and that really—that lake really makes Camp Todd what it is.

Inability to host water-related activities during peak season severely impacted Camp Todd's operation budget. During the summer of 2011 when blooms were at their worst, camp management was forced to invest limited resources in alternative programming, including transporting campers to other sites for water-based activities and developing less popular land-based programs. Camp registrations dropped as a result, as discussed by one key informant:

> They've heard about [the HABs] and… you know, anybody that calls to register, any adult, troop leader—we have to tell them that they can't use the waterfront and then there's kind of a drawback. They'll say, well, we need to think about it. …So the usage is down.

In response to the Girl Scouts' request for assistance, MDDNR convened an expert Task Force composed of regional and local scientific and policy experts established to advise the Girl Scouts on government efforts on HAB prevention, control, and mitigation measures. As

lake owners, the Girl Scouts' prioritized strategies that were inexpensive, scientifically sound, and capable of quickly restoring the lake to swimmable levels. Barley straw (*H. vulgare*) mitigation and lake drainage were approaches discussed with the Task Force. Reducing the lake's water levels through the manually controlled dam came at no cost and could be completed during off-seasons. Barley straw mitigation could be conducted for a minor cost of $2000 (US) for 500 bales and volunteer labor. The combined approaches were promising for ensuring lake usability in time for the following summer camp season.

In addition to their own concerns, the Girl Scouts also sought to restore use for lakefront landowners in order to mend relationships tarnished by past camp-imposed access restrictions, following a swimming accident that resulted in legal actions against the Girl Scouts in the 1990s. The Girl Scouts made special efforts to include local residents in mitigation discussions and invited them to use camp property for recreational needs (e.g., walking nature trails) while the lake remained unusable. This outreach helped rebuild important relationships integral to shaping landowners' responses to the lake HABs.

Lakefront landowners

Access restrictions were a primary concern for lakefront landowners, many of whom purchased adjacent property to enjoy the lake's recreational amenities and natural beauty. When *M. aeruginosa* blooms first appeared, many expressed concerns about HAB impact on their property values and recreational interests. Some landowners' attitudes were underpinned by tensions from the aforementioned camp imposed restrictions, and many wanted assurance that the Girl Scouts would not unnecessarily restrict their access. Some landowners expressed concern about associated health effects on their pets. These concerns were prompted by a report about two dog deaths linked to *M. aeruginosa* exposure at a nearby lake (Higgins Mill Pond) with severe blooms and a report about a dead deer found near Williston Lake (though the deer's death was not positively linked to *M. aeruginosa* exposure). Others had little concern about reported health risks as a result of previous benign experiences with what they perceived to be the same type of blooms.

Most of the landowners attended a Girl Scouthosted meeting organized to explain access restrictions, share mitigation plans, and enable the lakefront community to voice concerns and provide feedback. Some attendees were concerned about how lake drainage would impact their properties. A few expressed contentious attitudes attributed to their negative history with the Girl Scouts. However, most in attendance were generally supportive of the proposed mitigation. One resident shared his thoughts on the meeting:

> I'm glad they presented something…. I listened equally to the experts and then some of the neighbors. The neighbors have some concerns, whether they're appropriate or not, but I think by and large I was pretty satisfied with what they had to present, and basically satisfied with the response. … I really can't find fault with what's being presented as we're just joint partners or neighbors in it.

Lake drainage and barley straw mitigation were successful from the perspective of lakefront landowners in that it restored access to the lake. In 2012, one local resident reported that her husband returned to doing routine one-mile swims, an activity that he was not able to do

since 2010 due to the blooms. Others celebrated the return of wildlife and the lake's restored natural beauty.

Farmers

Farmers largely engaged in discussions to reduce blame on the agricultural community. Past experiences with increased regulation following the 1997 *P. piscicida* events (previously discussed) heightened concerns that the Williston Lake blooms would similarly lead to new regulations for local farmers. As one farmer explained:

> I think the farming community will do anything they need to. I don't know if you know anything about *Pfiesteria,* but *Pfiesteria* was a problem because there was a massive overreaction. And I think people are a little afraid of the overreaction and they want someone to blame, so they blame the farmers, even though [the nutrients in Williston Lake is] 100 years old and the farmers around here are doing everything that they're supposed to be doing [to reduce agricultural nutrient runoff].

In a separate conversation, another farmer expressed similar fears, using her memory of *P. piscicida* to frame her understanding of *M. aeruginosa* and to anticipate reactions from other stakeholders:

> I think the thing that worries me about the *Pfiesteria* is that so many claims were made and so much misinformation went out without research and it was a scare. It was just like everybody running around saying the sky is falling, and it really hurt a lot of people. That doesn't need to happen. What we need to do is go logically and quickly solve it [the Williston Lake blooms].

Both of these key informants also spoke about their contributions to regional nutrient reduction goals, stressing that local farmers were implementing some of the most rigorous best management practices (BMPs) to reduce nutrient and sediment runoff from their lands, and pointing to legacy sources of nutrients to explain the blooms. One local agricultural extension agent, a farmer himself, reinforced these views in reflecting on his surprise and frustration that the local farmers were being blamed for the lake HABs:

> [T]hat's the most wooded watershed that we've probably got in the County! Of all places I wouldn't have ever expected it there.… Shortly thereafter that's when I heard about people blaming agriculture and that's when I said the farmers that are farming that watershed are doing as good as anywhere. I guess I was a little perturbed that ag[riculture] was being blamed.

Others similarly expressed defensive attitudes, suggesting that farmers at Williston Lake were largely responding to reactions and anticipated reactions of other stakeholders capable of holding them legally and economically responsible for nutrient inputs to the lake.

Ironically, it was a local farmer who proposed barley straw mitigation as a solution for Williston Lake, demonstrating how he successfully abated cyanobacteria growth in his irrigation pond. Some Task Force members were initially skeptical of barley mitigation due to limited data and questions about its applicability at larger scales. One environmental professional suggested that this skepticism might have resulted from misgivings about farmers' lack of scientific knowledge.

Environmental professionals

Environmental professionals from government and non-government organizations with regional interests in Chesapeake restoration participated in the mitigation discussions through the Task Force. Many viewed Williston Lake as a case study of Chesapeake Bay-wide eutrophication problems and an opportunity to test new nutrient-reducing BMPs for regional application. As expressed by one key informant: '[If] we can do it [at Williston Lake], then we can show that we can do it in a larger area too…. And to me, that's what's exciting.' These stakeholders tended to advocate for long-term management approaches to establish more permanent nutrient controls as opposed to temporary mitigation approaches pursued by the local community.

The Task Force also included environmental professionals engaged in the Chesapeake basin-wide Total Maximum Daily Load (TMDL) compliance, a US government regulatory mandate implemented in 2010 by the U.S. Environmental Protection Agency (EPA). The TMDL compliance was established after the seven state jurisdictions within the Chesapeake Bay Watershed (including Washington D.C.) failed to sufficiently improve the Bay's water quality through 25 years of voluntary restoration programming. The TMDL regulation enforces Federal clean water standards for the Chesapeake Bay through the implementation of a 'pollution diet,' which requires State governments to implement appropriate nutrient and sediment controls in order to meet designated limits to phosphorus, nitrogen, and sediment entering the main- stem Chesapeake Bay tidal tributaries. The TMDL compliance is being implemented through three phases. First, each state government develops a watershed implementation plan (WIP) to identify specific nutrient reduction goals for their areas. After review and approval by EPA, WIPs undergo a revision in the second phase, where local governments identify strategies to implement their state's WIP. By 2017, each state is expected to have 60 % of practices in place, and 100 % by 2025 (the third phase).

The second phase of the Maryland WIP was in development when the Williston Lake blooms occurred. Maryland selected Caroline County as a site to pilot BMPs for their WIP, and with the onset of the *M. aeruginosa* blooms, Caroline County's local government officials pursued Williston Lake as a site for WIP demonstration. One county official recounted her excitement in learning about the lake blooms:

> We had just within the last week been talking about getting [a local soil scientist] to come look at some of our stuff and see if there was a small watershed that we could maybe go in with one of his technologies, and also look at some septic BMPs. And then [the camp ranger] walked in. …So I called [the soil scientist], told him the situation with the lake problem. … He was looking for the opportunity to do this on a whole larger scale, like a watershed scale. And all of this was being talked about when [the camp ranger] walked in with a [phosphorus] problem. I think I literally ran all the way to him, ''you're not going to believe this!''

Local government enthusiasm shifted after learning that nutrient reductions made at Williston Lake would not contribute toward meeting TMDL mandated reductions. As the same key informant explained:

> …There were some people, you know, people with scientific knowledge who—they'd say to me, you know, get out of there, you have no business being in there, that is not part of the TMDL because—it's a water body, but it's really not in terms of the receiving waters we're being told to clean up. The receiving waters are rivers. So it doesn't really factor into the TMDL directly in that it's not a direct impact to the receiving waters we're bound to clean up.

Scientists

Scientists with expertise in aquatic and wetland ecology also engaged in mitigation discussions as part of the Task Force. Some (specifically coauthors Sellner and Place) viewed the Williston Lake blooms as an opportunity to test clay flocculation mitigation for controlling Chesapeake Bay HABs. One recognized benefit of clay flocculation is its potential contribution toward TMDL-induced water clarity improvement goals through chlorophyll-*a* reductions. However, there was also concern that clay flocculation could be rejected by management communities because it necessitated the addition of sediment, which Chesapeake watershed jurisdictions are required to reduce in the TMDL regulation.

Similar to environmental professionals, scientists also stressed a need to reduce nutrient inputs, but acknowledged the difficulties of effectively identifying and controlling diffuse (non-point) sources into the lake. Scientists also noted the challenges of balancing recreational end-user needs with nutrient regulation, which became more apparent after working closely with the Girl Scouts. One researcher facetiously suggested:

> .… If we're worrying about the Bay, then allow these lakes to go green, because it removes most of the input ultimately. That's an interesting treatment option [laughs]. Let it go green. Keep away, don't go here, but at least the nutrients will be gone [from the Bay].

Many scientists supported a combined approach of nutrient management and mitigation in order to accommodate the Girl Scouts' needs while encouraging long-term reductions in base nutrient enrichment causing the blooms. Scientists also voiced concerns that the Girl Scouts may have unrealistic expectations in scientists' capacity to guarantee success. As one key informant stated,

> I don't think there is an easy fix, and we've told [the camp ranger] before that this isn't a problem that we promise is gone in 5 years. You know? We can't make that promise unless nutrients aren't coming in as much as they are.

Ecosystem science results

The lake's response to hydraulic flushing/bottom freezes and barley straw deployment was dramatic (Sellner et al. 2015). In 2012–2013, *M. aeruginosa* did not appear in the lake until mid-to-late August, and when it did it yielded toxin levels below those that trigger State recreational use advisories, allowing the Girl Scouts to use the lake throughout the summer. Cell numbers were substantially reduced from 2010–2011 abundances of 10^7 mL^{-1}, approximating 10^4 mL^{-1} in 2013 (see Fig. 1 in Sellner et al. 2015). Microcystin levels similarly declined from $>10^3$ ppb in 2011, to <6 ppb and at most to <1 ppb. The declines were likely due to a combination of flushing/ bottom freezing of the lake's overwintering

inoculum and barley straw deployment: (1) cores from the drained lake enriched with BG11 medium and slowly exposed to increasing light and temperature (to 28.5 °C) over a month showed resulted in no growth of the cyanobacterium in a final emergent flora, indicating the effectiveness of either or both shear stress in removing over-wintering populations and/or lysing populations via ice crystal formation; and (2) as noted in laboratory exposures of *M. aeruginosa* to *H. vulgare* extracts from the field (Fig. 3 in Sellner et al. 2015), decomposition products of deployed barley straw effectively inhibited summer growth of cyanobacterium. An added benefit was the emergence of a small (1-hectare) wetland at the mouth of one of the two incoming streams, important in nutrient and sediment removal in many systems (e.g., Craig et al. 2008; Weller et al. 1996). This lake-wide success was at least partially attributed to the rapport established as a result of the multi-stakeholder dialog described above, which helped convince the lead Girl Scout ranger and regional administrator to implement the flushing and barley straw mitigation strategies.

Discussion

The results from this study emphasize the importance of developing an interdisciplinary approach (the SES framework) for HAB research and management. First, by approaching HABs within a SES framework, it became clear how humans and ecosystem dynamics interacted to affect outcomes from the 2010–2011 *M. aeruginosa* blooms at Williston Lake (see Fig. 4). Diverse stakeholders with a variety of political, socioeconomic, and cultural concerns about lake access, nutrient management, and Chesapeake Bay restoration ultimately shaped the selection and implementation of barley straw mitigation and lake drainage. Ecosystem response to these interventions resulted in a reduced population of *M. aeruginosa* cells, thus enhancing water clarity, eliminating toxin threats, and enabling pre-bloom human–environmental dynamics to be restored during the summers of 2012–2013. Selected interventions, however, did not target nutrient inputs to the system, thereby sustaining a potential driver for future bloom events if annual mitigation activities are not implemented or conducted at inappropriate times. Barley straw mitigation, for example, has to be done during a certain window in the spring in order for its degradation products to inhibit *M. aeruginosa* cell growth (Sellner et al. 2015) and it does not inhibit all cyanobacteria (see references in Spencer and Lembi 2007). Alteration to broader ecosystem processes (e.g., warmer water temperatures or reduced winter freeze cycles due to climate change) could also render mitigation approaches ineffective, leaving Williston Lake and the surrounding community vulnerable to future bloom events (Najjar et al. 2010; Paerl and Huisman 2008); as could changes to human systems (e.g., development of surrounding agricultural lands or new regulatory activities). These examples highlight the importance of considering HABs in a social-ecological context in order to assess how feedbacks between human response and ecosystem response affect the short- and long-term health of the lake.

Consideration of spatial and temporal dimensions of response to HABs was also important for understanding the range of scalar interests and concerns shaping decision-making processes. From a human systems perspective, the concerns and interests of Williston Lake stakeholders were situated within a range of local and regional institutions that reinforce certain values, practices, and perspectives. Local and State government officials and environmental managers, for example, responded to the Williston Lake blooms through a

highly political lens institutionalized by federal, state, and local government agency directives, policies, and programs. This influenced these stakeholders to view the lake blooms within the context of broader Chesapeake environmental governance practices (e.g., TMDL compliance implementation) and priorities (e.g., water quality). The Girl Scouts organization, as a local cultural institution, helped reinforce local recreational practices and environmental values that led many to prioritize the restoration of lake access. These orientations in turn influenced the temporal scope of various mitigation preferences. While the lakefront community desired an immediate solution to restore lake usage, environmental professionals prioritized long-term nutrient management to improve the lake's water quality. Temporal dimensions of memory and past experiences also heavily influenced how stakeholders framed the HABs in important ways that affected their response. This is readily observed in how farmers framed the lake HABs within reflections on the political and economic hardships they incurred following the 1997 *P. piscicida* events; as well as with how lakefront landowners framed health advisories and closure within memories of past use-conflicts with the Girl Scouts. Studying the spatial and temporal dimensions of human response to HABs was critical for guiding the ecosystem mitigation research, as it provided researchers with a better understanding of social barriers to interventions and how to navigate around these barriers in order to restore pre-bloom human– environmental dynamics.

Using an interdisciplinary orientation guided by the SES framework also enabled us to identify key decision-makers and therefore understand why particular interventions were likely to succeed. At Williston Lake, there were four influential individuals in the network of stakeholders that emerged following the 2010–2011 HABs. The lead ranger of Camp Todd was the most influential decision-maker as the individual responsible for making the final decision about which mitigation strategy the Girl Scouts would fund. He also played an important role in funneling new information to the local community about *M. aeruginosa*, associated health risks, and the relationship between nutrients and HAB formation. Additionally, he provided ecosystem scientists with access to the lake for testing new mitigation approaches for regional applicability. A second key decision-maker was the state government representative who convened the Expert Task Force, thereby connecting the Girl Scouts with experts in HABs and nutrient management. On the Task Force was a third important decision-maker, a local County government official responsible for developing Caroline County's TMDL Phase II WIP demonstration. Through this individual, Williston Lake quickly became part of a larger discourse tied to Chesapeake Bay regional policy and environmental regulations. While the TMDL compliance demonstration was never carried out at Williston Lake, discussions offered important insights on the benefits of long-term nutrient management now being considered by the Girl Scouts for future interventions. Finally, the fourth key decision-maker was a neighboring farmer, who connected researchers and the lakefront community to the surrounding agricultural community, and provided important knowledge about barley straw application that informed decision-making about lake mitigation. Each of these individuals played a critical role in directing who engaged in discussions, shaping how knowledge was shared and developed, and establishing priority needs for intervention.

Engaging in interdisciplinary research at Williston Lake was critical for identifying opportunities to overcome key challenges to effective HAB mitigation. At the start of this project, the ecosystem science researchers (Sellner and Place) were concerned that intervening at Williston Lake could become contentious as a result of regional skepticism that scientists are part of a regulatory community forcing local land users to implement practices inconsistent with local agricultural and development interests. Hence developing an understanding of how knowledge, values, beliefs, and practices influence Williston Lake stakeholders was critical for developing and implementing effective HAB mitigation. By assessing perceptions of ‘algal blooms’ or ‘scum’ and underlying social factors that affected stakeholder response to mitigation, ecosystem science research could more effectively engage with local stakeholders in open dialog about HABs and other environmental concerns, including future options for reducing nutrient and sediment loads to the lake.

Conclusion

Harmful algal blooms are the result of complex environmental and human dynamics. Past HAB research has been predominantly ecological in focus, with limited social science research that has tended to focus on cultural knowledge and practices influencing health outcomes from HAB toxin exposure (Bauer 2006). All indications suggest that HABs will be increasing in the future, not only in number but also in the synergistic complexity of ecological and social factors. It would not be unproductive for the ecological and social sciences to individually investigate the drivers and consequences of HABs and mitigation efforts. Particularly in the social sciences, HABs are a relatively new environmental problem and the small number of researchers engaged in HAB research could profitably focus their energies on only the cultural, socioeconomic, and political factors to explain occurrence and responses to HABs. No doubt, a similar argument could be made for the ecological sciences. There is always value for core disciplinary work on environmental problems, including HABs. Furthermore, interdisciplinary work is conceptually challenging, requiring significant time and effort, and often ‘uncomfortableness’ as researchers extend themselves beyond the boundaries of their disciplinary beliefs and practices. There are significant epistemological challenges, and often the ultimate payoff in advancing research may emerge only late in the research process.

Nonetheless, there is also little doubt that future HAB research would benefit from integrated social and ecological research. Anthropogenic factors are the major reason for increasing HAB occurrence (see Anderson et al. 2002), and these factors extend well beyond the local human population that resides in and around the physical locations of HABs. Future HAB research should include a focus on local stakeholders, socioeconomic and health risks, and education efforts to reduce exposure and address local practices affecting the incidence and prevalence of HABs. However, it should also investigate broader spatial and temporal dynamics affecting bloom formation, as local stake- holders often have little influence or control over the ultimate cultural, socioeconomic, and political factors promoting HABs. These include long-term land use practices, increased population densities, changing uses of natural resources (particularly water), and increased generation of a range of pollutants into soils and waters. Ultimately, there needs to be a focus on both

local and extra-local factors, including how they converge to create research priorities and opportunities for HAB prevention, control, and mitigation.

The case study presented in this paper is an example of the processes that ecological and social scientists explored to collaboratively investigate a HAB and to work with stakeholders to develop mitigation efforts. The social science component provided guidance to ecological research on identifying the relevant local and regional stakeholders and institutions that affect and are affected by the Williston Lake blooms. Throughout the study, the cultural, socioeconomic, and political factors were key in explaining why particular individuals and groups were concerned about HABs and how each could influence ecological research and mitigation efforts. In the end, both the understanding of the ecological problem and its solution were influenced by input from social science findings on local stakeholders and regional institutions and processes. Conversely, the ecological research grounded the social science investigation to focus on the human links to key ecological processes of the HAB and its mitigation. Ecological research increased understanding among social scientists and Williston Lake stakeholders of how local knowledge and land use practices, past and present, can cause blooms and also contribute to mitigation (e.g., barley straw).

Future integrated social and ecological research on HABs will no doubt identify different sets of ecological and social drivers and consequences. Such research will allow further development of a SES framework for HAB research. Also of great benefit will be the practical outcomes: lessons learned on integrating stakeholders and institutions in HAB management, more productive communication between researchers and the communities they engage with, and increased awareness of the relationships between human activities and ecosystem responses. These will not only strengthen prevention, control, and mitigation initiatives, but also hopefully reduce the presence of harmful algae.

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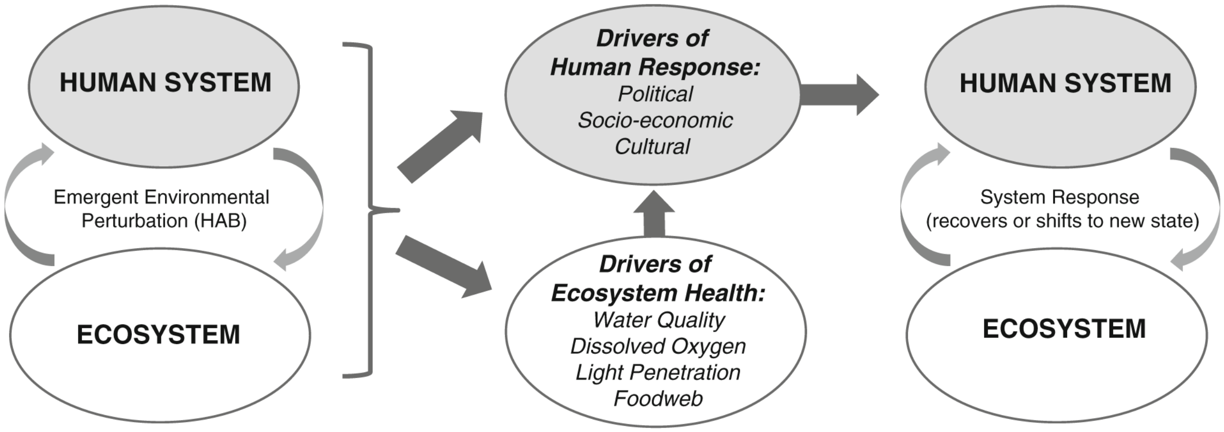

Fig. 1.

A socio-ecological system framework developed to inform interdisciplinary study of HABs. HABs emerge in the context of complex, multi-scalar human and ecosystem interactions (*left*). The emergence of a bloom affects key drivers of ecosystem health and triggers humans to respond through a range of cultural, political, and economic motivations (*center*). Response from the human system triggers ecosystem change, which feeds back into human system dynamics to shape how the overall system responds, either by recovering from the HAB and returning to initial pre-bloom state, or by shifting to a new state (*right*)

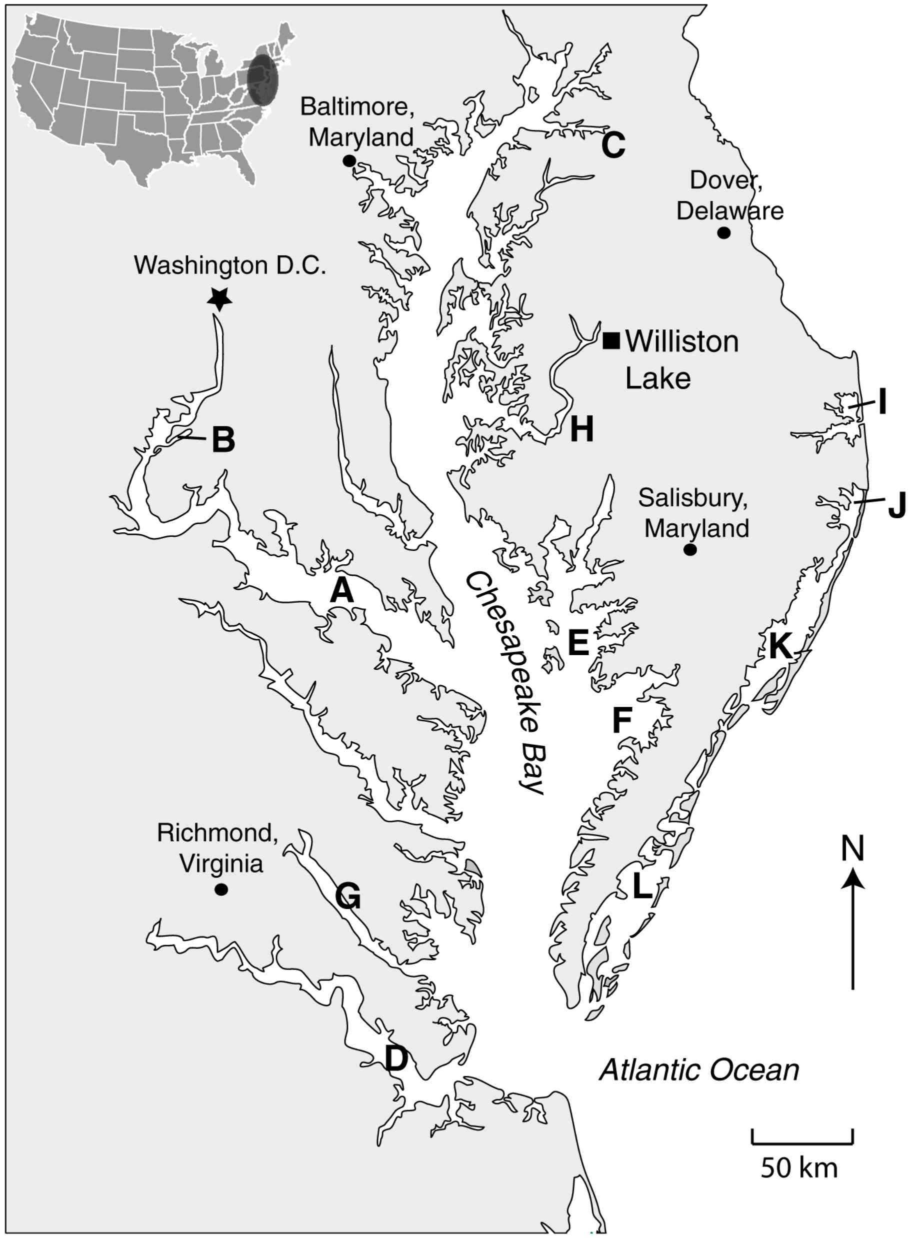

Fig. 2.

HAB locations in the Chesapeake Bay identified in the text: (*a*)Potomac River, (*b)* Mattawoman Creek, (*c*) Sassafras River, (*d*) James River, (*e*) Nanticoke Sound, (*f*) Pocomoke Sound, (*g*) York River, (*h*) Choptank River (located near the study setting, Williston Lake); and (*i*– *l*) Eastern Maryland coastal lagoons (map adapted from Saxby 2011 and 2003)

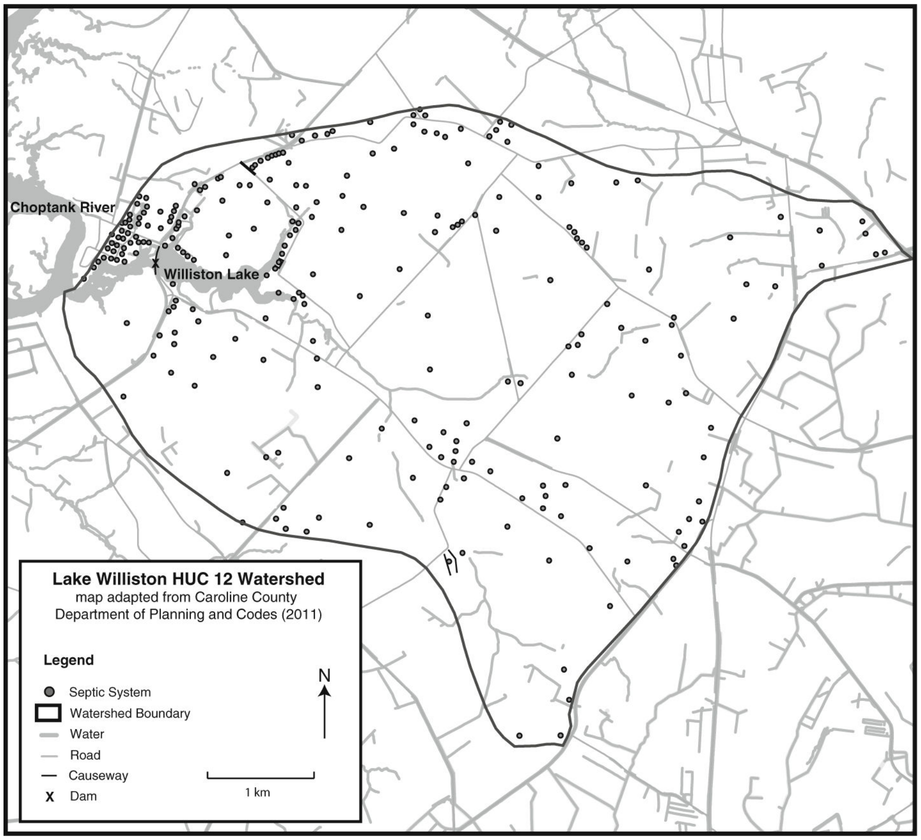

Fig. 3.

Map of the Williston Lake HUC 12 watershed, with surrounding septics (adapted from Caroline County Department of Planning and Codes (2011))

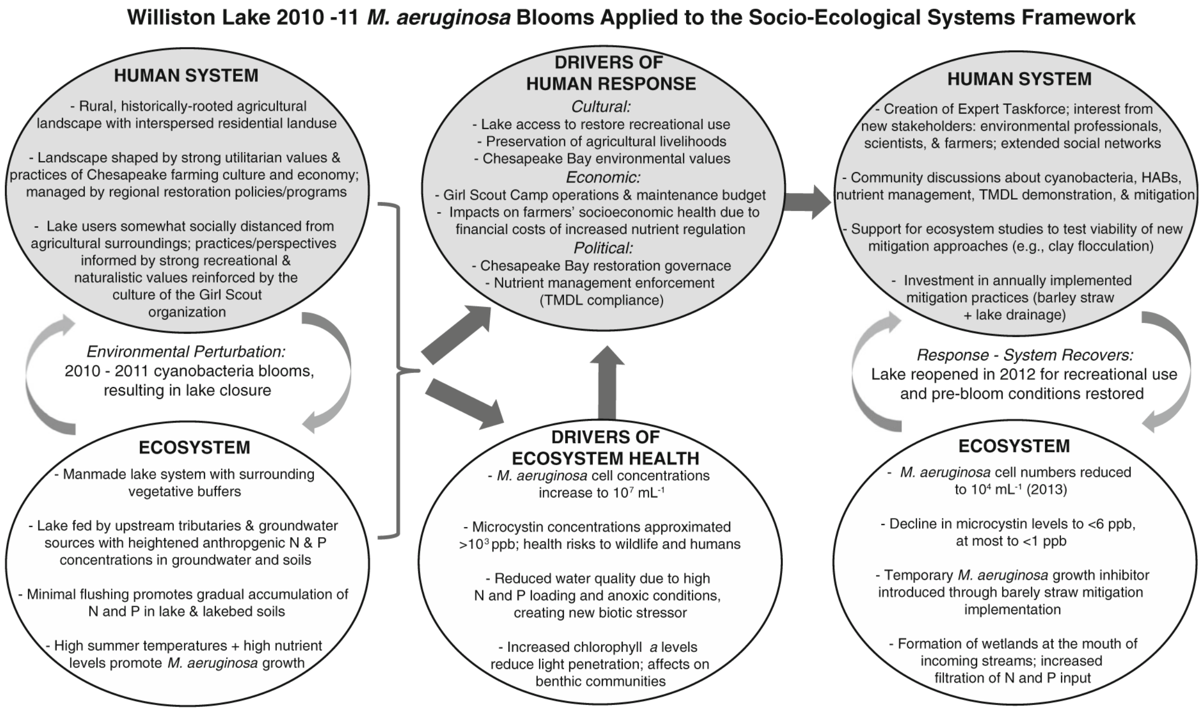

Fig. 4.

Socio-ecological systems framework applied to Williston Lake. The *left side* of the diagram represents the range of human system and environmental system dynamics, each interacting across various spatial and temporal dimensions to create the 2010 and 2011 Williston Lake *M. aeruginosa* blooms that closed the lake. The emergence of the blooms affected key drivers of ecosystem health, and motivated human response through a range of cultural, economic, and political drivers (*center*). Declines in ecosystem health further motivated stakeholders to react to the blooms in particular ways (*center*). Human responses (*right*) affected changes to ecosystem health, which fed back into the human system to reinforce new behaviors and practices. Feedbacks between human system response and ecosystem response resulted in overall system recovery in 2012–2013 (*right*)