



Assessing Risk for Enhanced Cyanobacteria, Phytoplankton, and Pathogens with Changes in Water Level Regime with Potential Application to Lake Powell and Lake Mead

A Mixed Methods Literature Review



A bloom of the cyanobacterium *Microcystis aeruginosa* in the spring and summer of 2015 caused parts of Lake Mead reservoir to turn bright green.

U.S. BUREAU OF RECLAMATION

Assessing risk for enhanced cyanobacteria, phytoplankton, and pathogens with changes in water level regime with potential application to Lake Powell and Lake Mead: A mixed methods literature review

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Contents

	Page
Figures.....	v
Tables.....	vi
Abstract.....	vii
Acknowledgments.....	viii
Executive Summary	ix
Introduction.....	1
Methods.....	4
Mixed-Methods Literature Review	4
Rapid Literature Review.....	4
White and Gray Literature Review.....	12
Statistical Analysis of Studies in the Rapid Literature Review.....	12
Characterization of Studies Analyzed for Rapid Literature Review.....	14
Responses to Water Level Changes	17
Phytoplankton and Cyanobacterial Responses	17
Findings from the Literature Review	17
Statistical Analyses.....	21
Chi-square Tests	21
Logistic Regression	22
Characterization of Studies Identified by Agency Search.....	23
Case Studies	24
Cochiti Reservoir (Sandoval County, New Mexico).....	24
Blue Mesa Reservoir (Gunnison County, Colorado).....	24
Other Pathogens.....	25
Highlighted Studies of Particular Relevance to Lake Powell and Lake Mead	27
Management and Monitoring Goals	29
Limitations of this Analysis	31
Future Directions	32
Conclusion	33

Contents (continued)

	Page
Literature Cited	34
Appendix.....	42

Figures

	Page
Figure 1. Flow chart showing the literature review process.	6
Figure 2. Bar chart showing relevant management concerns contained in the reviewed studies.	14
Figure 3. Bar chart showing relevant management strategies contained in the reviewed studies.	15
Figure 4. Bar chart showing distribution of trophic status of waterbody sampling events (n = 49) in the reviewed studies.	16
Figure 5. Map of reported waterbody location by country and latitude and longitude (denoted by black dots and pink diamonds).....	16
Figure 6. A bar chart showing the number of waterbody instances exhibiting different phytoplankton responses to a decrease in water level.....	18
Figure 7. A bar chart showing the number of waterbody instances exhibiting phytoplankton responses to an increase in water level.	19
Figure 8. Bar chart showing cyanobacterial responses to decreases in water level.	20
Figure 9. Bar chart showing cyanobacterial response to increases in water level.	20
Figure 10. Analysis of phytoplankton responses to waterbody water level fluctuation, as reported in the literature.	21
Figure 11. Analysis of cyanobacterial responses to waterbody water level fluctuation as reported in the literature.	22
Figure 12. Two logistic regressions show the likelihood that cyanobacteria and phytoplankton will increase due to water level change.	23

Tables

	Page
Table 1. Inclusion and exclusion criteria for the rapid literature review.....	5
Table 2. Waterbodies included in this literature review that exhibited either a water level increase or decrease.	7
Table 3. Trophic state categorization (Carlson 1977).	13
Table 4. A description of each of the studies included in this review, the number of waterbodies in each study, reported management strategies or concerns, and reported response variables.	42

Abstract

Water levels in freshwater reservoirs worldwide are changing due to altered climate, management practices, and increasing human demand for water. In the desert southwestern USA, managers are considering significant changes to reservoir operation strategies and water management in response to consumptive use and ongoing drought. To inform reservoir management decision-making, we reviewed current peer-reviewed literature to identify the effects of decreasing or increasing water level on phytoplankton, cyanobacteria, *Escherichia coli*, and *Naegleria* spp. We identified 34 studies containing 42 individual waterbodies that investigated the effects of water level increases or decreases on phytoplankton or cyanobacteria. We found that water level decreases resulted in a higher likelihood of increased cyanobacteria, and that phytoplankton were more likely to decrease in response to water level increases. Most of the waterbodies included in the literature review were eutrophic or hypereutrophic, underscoring the need to explore the effects of water level fluctuations on oligotrophic systems. We only identified five studies on *E. coli* through our review, and no studies on *Naegleria* spp. We supplemented our review with regional white papers and case studies within the Colorado River Basin and the Rio Grande River Basin to highlight relevant research. Prior and ongoing research highlights the need to explore impacts of water level fluctuations on phytoplankton and cyanobacteria to guide future management decision-making.

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Executive Summary

Water levels in freshwater reservoirs globally are changing due to altered climate, management practices, and increasing human demand for water. It is estimated that over half of seasonal freshwater storage variability on Earth occurs in human-managed reservoirs (Cooley et al. 2021), yet the water quality consequences of this variability are largely unknown. This report is motivated by long-term reductions in water level in Lake Powell and Lake Mead reservoirs and a need to understand the impacts of water level fluctuations on key water quality variables: phytoplankton and cyanobacteria, *Escherichia coli*, and *Naegleria fowleri*. In response, we conducted a literature review of papers that quantified how both natural and anthropogenic changes in waterbody hydrology affected phytoplankton and cyanobacterial biomass and composition, as well as two pathogens of concern, *E. coli* and *N. fowleri*. Throughout this report, the term waterbody refers to lakes and reservoirs. Our literature review through the Web of Science database returned 733 papers that included our focal keywords in their title or abstract (see Methods for search terms). Of those 733 papers, 36 papers (providing information on 42 individual waterbodies) fit the criteria for this review. The 36 papers contained information about water quality in waterbodies deeper than ten meters that experienced a drought or drawdown for longer than three months or were managed with a relevant management strategy (e.g., epilimnetic flushing, etc.). Of the 36 papers, 34 measured phytoplankton and/or cyanobacteria, 2 focused on *E. coli*, and no studies included *N. fowleri*. Most of the studies included in this literature review were concerned with managed and unmanaged drought and water level drawdown, but a few studies also discussed reservoir refill, flushing, and selective withdrawal. The waterbodies included in this analysis spanned all trophic states, ranged from 17 to 372 meters deep, and had surface areas between 2 and 4,500 km². Of the 24 cases in which cyanobacterial dynamics were measured during water level drawdown, 21 reported significant increases in cyanobacteria (while 2 reported a decrease, and 1 found no change). Of the 25 cases in which phytoplankton dynamics were measured during water level increases, 19 reported no increase in phytoplankton (while 6 reported increases). Chi-square tests showed that these responses were statistically significant: cyanobacteria were significantly more likely to increase in response to decreases in water level, and phytoplankton were significantly less likely to increase in response to increases in water level. Logistic regression demonstrated that larger decreases in water level were correlated with phytoplankton and cyanobacterial increases, though this finding was not statistically significant. This non-significant result is likely due to our limited sample size, as only 14 phytoplankton and cyanobacterial studies included information on both the magnitude of water level change and maximum depth. We supplemented our Web of Science literature review with a search for relevant U.S. National Park Service and U.S. Geological Survey reports, as well as a case study from Blue Mesa Reservoir, where there is ongoing work to characterize recent cyanobacterial blooms and their environmental drivers (K. Walton-Day, U.S. Geological Survey, written communication, July 26, 2024). Given the limited number of studies on water level fluctuation effects on *E. coli*, we also included three additional studies examining *E. coli* dynamics in reservoirs that were screened as part of our formal review but that did not meet the formal inclusion criteria of the literature review analysis. These three *E. coli* studies reported associations between pathogen prevalence and human activity, as well as rainfall regime, but did not specifically link water level fluctuations to *E. coli*

patterns. Overall, our review suggests that the prevalence of cyanobacteria increases when reservoir water levels decline. Thus, reservoirs undergoing more severe water level fluctuations and/or declines may be at increased risk for cyanobacterial blooms.

Introduction

Water quality plays a critically important role in determining the health of aquatic species and the suitability of water for drinking, recreation, and irrigated agriculture (Jones and Smol 2023). Water level fluctuations can cause large changes in reservoir water quality by altering fundamental aspects of waterbody mixing (such as the total volume of water, the height of water release, and the ratio of warm surface water vs. cold bottom water), and by entraining suspended sediment and nutrients, which can change salinity, light availability, and algal, cyanobacterial, and other microbial dynamics (Zohary and Ostrovsky 2011, Lewis et al. 2024). Despite these potentially negative consequences, drawdowns are increasing in many reservoirs in response to both altered climate and management, and the net effects of water level fluctuations on water quality are largely unknown because of the complex interactions that can occur as drawdown alters a reservoir's physical, chemical, and biological conditions (Lewis et al. 2024).

During the 21st century, the desert southwest United States has experienced one of the worst droughts on record, leading to a 19% decline in water runoff between 2000 and 2014 as compared to the 1906–1999 average (Udall and Overpeck 2017). The drought continues through the writing of this report (Wheeler et al. 2022). Many reservoirs in the Colorado River Basin have experienced large declines in water storage due to a combination of drought and consumptive water use (Wheeler et al. 2022; Schmidt et al. 2023). This has included a collective 33.5-million acre-foot decline in water storage in Lake Powell and Lake Mead, the United States' two largest reservoirs, between January 2000 and April 2023 (Schmidt et al. 2023). Reservoir storage declines have resulted in hundreds of feet of net water level decline in both reservoirs, with tens of meters of fluctuation from year to year (Schmidt et al. 2023).

Water level management in Lake Powell and Lake Mead is informed by a series of documents (see more details in Schmidt et al. 2023), several of which are scheduled to expire at the end of 2026 (U.S. Bureau of Reclamation 2023). An ongoing multi-year National Environmental Protection Act (NEPA) process is identifying a range of alternatives and will ultimately determine Colorado River Basin operations, the results of which could influence management for decades into the future (U.S. Bureau of Reclamation 2023). Here, we refer to this NEPA process as the Post-2026 Environmental Impact Statement (EIS). The two primary reservoirs being evaluated for the Post-2026 EIS are Lake Powell (part of the Glen Canyon National Recreation Area) and Lake Mead (part of the Lake Mead National Recreation Area). These National Recreation Areas (NRAs) are managed by the National Park Service (NPS) to meet the NPS mission to “preserve unimpaired the natural and cultural resources and values of the National Park System for the enjoyment, education, and inspiration of this and future generations.”

The NRA designation was originally given to areas that surround Bureau of Reclamation reservoirs and feature water-based recreation and has since been used for recreational units in or near urban centers (Comay 2023). Per the enabling legislation of the Glen Canyon and Lake Mead NRAs, all lands in the recreation area remain subject to the Bureau of Reclamation to operate in accordance with the Colorado River Storage Project Act for river regulation, irrigation, flood control, and

generation of hydroelectric power (An Act to establish the Glen Canyon National Recreation Area in the States of Arizona and Utah. Pub. L. No. 92-593, 86 Stat. 1311 (1972); An Act to provide an adequate basis for administration of the Lake Mead National Recreation Area, Arizona and Nevada, and for other purposes. Pub. L. No 88-639, 78 Stat. 1039 (1964)). This can be a difficult balancing act, as the Reclamation mission is still to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

The dynamic water level conditions in Lake Powell (Arizona/Utah, U.S.) and Lake Mead (Arizona/Nevada, U.S.) combined with the ongoing Post-2026 EIS motivate the need to better characterize how drawdown may be affecting these reservoirs' water quality, as well as identify potential future changes in response to different withdrawal scenarios. In Lake Powell, low reservoir water levels promote the development of low dissolved oxygen zones in the water column during the summer and fall, which has led to unprecedented low dissolved oxygen concentrations in the reservoir metalimnion and in dam releases (minimum mean daily dissolved oxygen was 1.8 mg/L and concentrations remained below 5 mg/L for 116 days in 2023; U.S. Geological Survey 2024). Lake Powell also fully mixed during the last two winters, leading to elevated salinity in springtime dam release waters (U.S. Geological Survey 2024) and unexplored effects on reservoir plankton assemblages. In Lake Mead, however, water quality has been relatively stable in the face of drought (Hannoun and Tietjen 2023). Large water level declines in Lake Powell and Lake Mead are coincident with the establishment of invasive Quagga mussels (*Dreissena bugensis*), which were first detected in Lake Mead in 2007 (Beaver et al. 2018) and in Lake Powell in 2012 (Deemer et al. 2023). Because Quagga mussels filter large volumes of water, they can have notable water quality effects (Reynolds and Aldridge 2021; Tang et al. 2014). Thus, Lake Powell is experiencing a period of dynamic water quality with its future trajectory determined by the degree to which the drought persists and by decisions about consumptive water use and water storage (e.g., how water is allocated between Lake Powell and Lake Mead; Wheeler et al. 2022).

Among water quality variables, a critical research need is to better understand how cyanobacterial dynamics will respond to changing water level conditions in Lake Powell and Lake Mead in the future. Cyanobacteria are photosynthetic organisms (e.g., phytoplankton) that can exhibit rapid growth in response to changes in temperature, light, nutrient, and salinity conditions in lakes (Huisman et al. 2005). If optimal environmental conditions occur, cyanobacterial biomass can increase over short time periods (hours to days), forming surface scums (blooms) that are associated with noxious odors and toxins that are harmful for humans or pets that swim or drink contaminated water (Carey et al. 2012, Chorus and Welker 2021). Moreover, the presence of Quagga mussels can also influence the dominance of cyanobacteria, with mussel presence being linked to both decreases in cyanobacteria (Reynolds and Aldridge 2021) and increases in cyanobacteria via selective feeding of Quaggas (Tang et al. 2014).

Cyanobacteria could increase or decrease in response to future changes in water level in Lake Powell and Lake Mead, motivating the need to 1) better characterize their responses to historical water level changes, and 2) predict how cyanobacterial populations may change in the future in response to alternate drawdown scenarios. For example, if drawdown decreases light availability in the water

column because of higher turbidity and sediment mobilization rates, which would reduce water temperature, cyanobacterial populations could decrease; conversely, if drawdown increases water temperatures and/or the availability of nutrients (especially of nitrogen and phosphorus), cyanobacterial populations could increase (Lewis et al. 2024). Preliminary observations from the long-term Lake Powell dataset (Deemer et al. 2023) suggest that the cyanobacterial community may be shifting over time to exhibit greater dominance by toxin-producing taxa, underscoring the need for studying how drawdowns affect cyanobacterial community composition and biomass. Lake Mead experienced a bloom of toxic cyanobacteria in 2015 following a warm winter with low snowpack (Beaver et al. 2018). Toxins are not currently monitored on Lake Powell, but Lake Mead is monitored for free and total microcystin concentrations regularly by Southern Nevada Water Authority (T. Tietjen, Southern Nevada Water Authority, written communication, September 19, 2024).

In addition to cyanobacterial blooms, changes in reservoir hydrology may also affect a suite of other water quality constituents. For example, human use in both reservoirs has led to detections of *E. coli* above safe limits in the past, although the establishment of floating restrooms (which are restrooms atop docks that allow easy boat access) as well as a larger effort to prohibit digging catholes near the lake and requiring houseboats to remove the ability to dump their holding tanks overboard largely alleviated the problem (G.M. Anderson, U.S. Geological Survey, written communication, July 17, 2024). If future changes to lake levels limit boat ramp access, there could be a recreational shift from larger motorized boats to smaller personal watercraft which would make the floating restrooms less accessible (given their relatively sparse locations). Similarly, in 2022, the Southern Nevada Health District confirmed a fatality due to an infection of *Naegleria fowleri* from the Kingman Wash area of Lake Mead (Osborne 2022). This was the first documented infection of the amoeba in Lake Mead and was surprising, as the species is commonly observed in warm freshwaters such as hot springs. *Naegleria* spp. are free-living amoebae that are found in freshwaters and soils and sediments, and are most prevalent in warmer waters (Detterline and Wilhelm 1991, Stahl and Olson 2021). Thus, to the extent that changes in water level may affect surface water and sediment temperatures, the probability of *N. fowleri* occurrence may also change.

Here, we present a rapid mixed methods literature review to synthesize studies of phytoplankton, cyanobacteria, *N. fowleri*, and *E. coli* in the context of long-term lake and reservoir water level fluctuations (such as those caused by drought). We note that water level fluctuations can have wide-ranging water quality effects, including changes to the nutrient, light and temperature environment which may directly affect our study organisms. However, given the short timeline required to inform the Post-2026 EIS, we limit the scope of this review to papers that quantify direct effects on the study organisms of interest. Thus, while there are many aspects of water quality that can influence ecosystem and human health, we specifically focused on variables of concern to managers that could inform the Post-2026 EIS process.

Methods

Mixed-Methods Literature Review

Rapid Literature Review

To synthesize the literature on the effects of drought and drawdown on phytoplankton blooms and pathogens in large reservoirs, we conducted a rapid review of existing peer-reviewed literature (following Grant and Booth 2009). We used the Clarivate Web of Science platform (<https://mjl.clarivate.com/home>) as our focal database. For the rapid review, we used a Boolean search to query Web of Science to find papers that contained terms about reservoirs, phytoplankton, toxic algal blooms, *E. coli* or *N. fowleri*, and that considered changes in reservoir water level or other relevant reservoir management strategies. This search returned 733 papers, which we further refined through Covidence, a literature review software (<https://www.covidence.org/>).

Boolean search terms for the rapid literature review:

```
ALL = (reservoir* OR impoundment) AND ALL = (phytoplankt* OR  
cyanobacteria OR naegleria OR "N. fowleri" OR "Naegleria fowleri"  
OR "E. coli" OR "Escherichia coli" OR chlorophyll OR alga* OR  
"blue-green alga*" OR bloom OR "harmful algal bloom" OR HAB OR  
HABs OR cyanoHAB* OR cyano-HAB*) AND ALL = ("water level" OR  
drawdown OR drought OR "water level fluctuation" OR "hydrodynamic  
control" OR "variable hydrology" OR "hydraulic flushing" OR  
"reservoir flushing" OR snowmelt OR "spring flow" OR "selective  
withdrawal" OR "hypolimnion spill" OR "epilimnion spill" OR  
"surface spill" OR "bottom spill")
```

The Covidence workflow had three steps, which we used to select papers returned by the search that were relevant to our review. The first step in the process was an abstract review of the 733 studies returned by our initial search. During this step, each abstract was reviewed by two people, who then decided to include or exclude the study. For the abstract review, abstracts were accepted if there was some mention of the biological variables of interest and water level change. Conflicts were addressed by a single reviewer according to the study criteria. If the study could not be excluded based on the information in the abstract, it was passed on to full text review. The second step was a full text review of the 276 studies that passed the abstract review. For this step we excluded papers from the review based on predetermined criteria (Table 1). For this review, we included papers that were focused on a lake or reservoir more than ten meters deep, doubling the five meter threshold between lake and pond identified in Richardson et al. (2022), had a surface area greater than five hectares (Richardson et al. 2022), and had three or more months of phytoplankton or pathogen data (e.g., chlorophyll *a*, community composition, cyanobacteria, *E. coli*, *N. fowleri*), in combination with water level or drought information. We excluded floodplain lakes, as well as studies that described the effects of specific management actions not relevant to Lake Powell or Lake Mead reservoirs (e.g., reservoir coverings, aquaculture, fish stocking or removal, aeration, chemical treatments, and/or sediment removal). Studies were also excluded if they examined water level fluctuations, but did not

quantify the direction or magnitude of the change (either as change in waterbody elevation or volume). The full text review also required the agreement of two reviewers, and conflicts were addressed as described above. While a body of literature has characterized water quality changes in reservoirs that undergo shorter-term water withdrawals (e.g., for flood control; Carmignani and Roy, 2017) and in shallow reservoirs (Matsuzaki et al. 2023), we developed these selection criteria to identify waterbodies that would function most similarly to Lake Powell and Lake Mead and had water quality measurements collected for at least three months (Table 1).

Table 1. Inclusion and exclusion criteria for the rapid literature review.

Parameter	Inclusion Criteria	Exclusion Criteria
Depth	More than 10 meters deep	Less than 10 meters deep
Surface area	Surface area is greater than 5 hectares	Surface area is less than 5 hectares
Data variables	Data collected primarily focus on a biological variable of interest (phytoplankton, chlorophyll <i>a</i> , cyanobacteria, <i>E. coli</i> , or <i>Naegleria</i> spp.)	Data collected does not focus on a biological variable of interest (including papers focused on characterizing trophic status)
Waterbody type	Data are from a lake or reservoir	Data are from a floodplain lake or is not from a lake or reservoir
Management strategy relevance	Study examines a relevant management strategy (drawdown, hydraulic flushing, changing withdrawal depth aka selective withdrawal, high flow releases) OR relevant management concern (water level fluctuation regime, droughts vs. wet years)	An irrelevant management strategy (e.g., fish exclusion, fisheries, metals).
Study length	Data were collected for at least three months	Data were collected for less than three months
Variable change	Paper addresses some change in biological variable of interest over time in response to a management strategy or concern (water level fluctuation regime, droughts vs. wet years)	Paper does not address change over time in response to a management strategy or concern
Water level change	Paper details the direction and/or magnitude of the water level change or fluctuation	Paper mentions water level fluctuation or water level change, but does not provide information about the direction of water level change
Peer review	Peer-reviewed	Not peer-reviewed
Language	Paper is in English	Paper is not in English

The final step was data extraction, in which we extracted data from each of the relevant papers to synthesize the current literature on the effects of water level fluctuations on phytoplankton, cyanobacteria, and pathogens in reservoirs (Figure 1). We extracted data to describe basic attributes of the waterbodies, the water level fluctuations they experienced, and the other relevant management strategies implemented during the study. We recorded waterbody trophic status based on what was reported in the study. If the study did not report trophic status, we characterized trophic status based on total phosphorus and chlorophyll *a* values, if reported (Carlson 1977). We also extracted study-specific information to determine the length and type of study, and the type of data that was collected from the lake or reservoir (see Appendix).

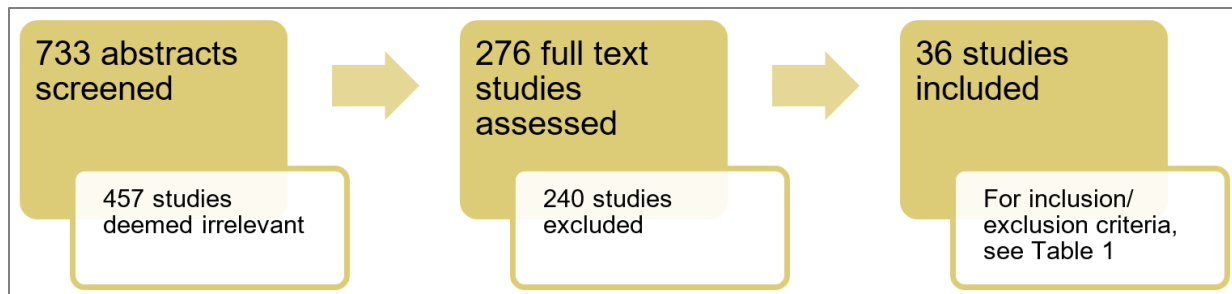


Figure 1. Flow chart showing the literature review process. NPS

We analyzed the 36 studies found through the literature review to characterize the responses of phytoplankton and cyanobacteria to water level increases and decreases in each reservoir (*E. coli* and *N. fowleri* were not statistically analyzed due to low sample size; Table 2). These responses were divided into four categories (increase in phytoplankton or cyanobacteria, decrease in phytoplankton or cyanobacteria, shift in phytoplankton or cyanobacteria communities, and no change or a not significant response) for analysis. For some statistical analyses, the “*shift in phytoplankton or cyanobacteria communities*” and the “*no change or no significant response*” categories were grouped together. Studies measured phytoplankton and cyanobacteria in several ways, and these measurements were grouped into either the phytoplankton or cyanobacteria categories.

Consequently, throughout this report, “phytoplankton” refers to any of the following metrics: chlorophyll *a*, phytoplankton biovolume, or phytoplankton biomass. “Cyanobacteria” refers to any of the following metrics: cyanobacterial biovolume, cyanobacterial biomass, or cyanobacterial toxins (Table 2; Appendix). We did not differentiate between metrics of measurement within groups.

Two papers about *E. coli* were included in the extracted papers. We combined these two papers with three papers about *E. coli* that did not meet our extraction criteria but were included in the full text review portion of our selection process. These five papers are discussed in the “Other Pathogens” section below. No papers about *N. fowleri* were identified in our review, but one paper was identified by the white paper search and is discussed in the “Other Pathogens” section below.

Table 2. Waterbodies included in this literature review that exhibited either a water level increase or decrease. NR = not reported.

Lake or Reservoir Name	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Trophic Status	Did water level increase or decrease?	Maximum water level change (m)	Did phytoplankton increase?	Did cyanobacteria increase?	Study ID
Acauã	Brazil	-7.44	-35.56	eu-hypereutrophic	decrease	N/A	not reported	no	Mendes 2022
Armando Ribeiro Gonçalves Reservoir	Brazil	-5.67	-36.9	not reported	increase	8	no	no	Câmara 2015
Armando Ribeiro Gonçalves Reservoir	Brazil	-5.67	-36.9	not reported	decrease	-9.5	yes	yes	Câmara 2015
Banabuiú	Brazil	NR	NR	not reported	increase	N/A	yes	not reported	Nunes Carvalho 2022
Banabuiú	Brazil	NR	NR	not reported	decrease	N/A	no	not reported	Nunes Carvalho 2022
Boqueirão	Brazil	-7.5	-36.14	eu-hypereutrophic	decrease	N/A	not reported	yes	Mendes 2022
Camalaú	Brazil	-7.88	-36.84	eu-hypereutrophic	decrease	N/A	not reported	yes	Mendes 2022
Castanhão	Brazil	NR	NR	not reported	increase	N/A	yes	not reported	Nunes Carvalho 2022
Castanhão	Brazil	NR	NR	not reported	decrease	N/A	no	not reported	Nunes Carvalho 2022
Danjiangkou Reservoir	China	32.73	111.56	eu-hypereutrophic	increase	24	no	yes	Pan 2018
Dongting Lake	China	28.86	112.69	not reported	increase	5.5	yes	yes	Yan 2023
Dongting Lake	China	28.86	112.69	not reported	decrease	-7	no	not reported	Yan 2023
El Gergal	Spain	37.57	-6.05	not reported	decrease	-10	no	not reported	Hoyer 2009
Eustis	USA	28.85	-81.72	eu-hypereutrophic	decrease	N/A	not reported	yes	Havens 2019

Table 2 (continued). Waterbodies included in this literature review that exhibited either a water level increase or decrease. NR = not reported.

Lake or Reservoir Name	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Trophic Status	Did water level increase or decrease?	Maximum water level change (m)	Did phytoplankton increase?	Did cyanobacteria increase?	Study ID
Fort Peck Lake	USA	48	NR	oligo-mesotrophic	increase	N/A	no	not reported	Beaver 2013
Harlan County Reservoir	United States	40.06	-99.29	not reported	increase	N/A	no	not reported	Olds 2011
Harlan County Reservoir	United States	40.06	-99.29	not reported	decrease	N/A	yes	not reported	Olds 2011
Harris	USA	28.78	-81.81	eu-hypereutrophic	decrease	N/A	not reported	yes	Havens 2019
Hongfeng	China	26.48	106.41	not reported	increase	6	no	no	Li 2018
Irkilinsky	Russia	51.68	58.62	oligo-mesotrophic	increase	2	no	yes	Dzhaiani 2020
Irkilinsky	Russia	51.68	58.62	oligo-mesotrophic	decrease	-2	no	no	Dzhaiani 2020
Joanes Reservoir I	Brazil	-12.57	-38.2	not reported	increase	N/A	not reported	no	De J. Magalhaes 2019
Joanes Reservoir I	Brazil	-12.57	-38.2	not reported	decrease	N/A	not reported	yes	De J. Magalhaes 2019
Karaoun Reservoir	Lebanon	33.57	35.7	not reported	increase	22	no	no	Fadel 2015
Karaoun Reservoir	Lebanon	33.57	35.7	not reported	decrease	-22	yes	yes	Fadel 2015
Kuibyshev	Russia	53.65	48.93	oligo-mesotrophic	increase	N/A	no	no	Khaliullina 2022
Kuibyshev	Russia	53.65	48.93	oligo-mesotrophic	decrease	N/A	yes	yes	Khaliullina 2022
Kuibyshev Reservoir	Russia	NR	NR	not reported	decrease	-5	yes	not reported	Khaliullina 2009

Table 2 (continued). Waterbodies included in this literature review that exhibited either a water level increase or decrease. NR = not reported.

Lake or Reservoir Name	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Trophic Status	Did water level increase or decrease?	Maximum water level change (m)	Did phytoplankton increase?	Did cyanobacteria increase?	Study ID
Lake Austin	United States	30.3	-97.79	oligo-mesotrophic	decrease	N/A	yes	yes	Bellinger 2018
Lake Buchanan	USA	30.8	-98.4	eu-hypereutrophic	decrease	-10.6	yes	yes	Gámez 2023
Lake Diefenbaker	Canada	51.03	-106.84	oligo-mesotrophic	decrease	-5.5	yes	yes	Abirhire 2019
Lake Diefenbaker	Canada	51.03	-106.84	oligo-mesotrophic	decrease	-3	no	yes	Abirhire 2023
Lake Francis Case	USA	43.1	NR	oligo-mesotrophic	increase	N/A	no	not reported	Beaver 2013
Lake Kinneret	Israel	32.83	35.58	oligo-mesotrophic	increase	4.7	not reported	yes	Bakker 2016
Lake Kinneret	Israel	32.83	35.58	oligo-mesotrophic	decrease	-4.7	not reported	yes	Bakker 2016
Lake Mead	United States	36.25	-114.39	oligo-mesotrophic	decrease	-40	not reported	yes	Beaver 2018
Lake Oahe	USA	44.5	NR	oligo-mesotrophic	increase	N/A	no	not reported	Beaver 2013
Lake Peipsi	Estonia	58.67	27.43	eu-hypereutrophic	increase	1	not reported	yes	Bakker 2016
Lake Peipsi	Estonia	58.67	27.43	eu-hypereutrophic	decrease	-1	not reported	yes	Bakker 2016
Lake Sakakawea	USA	47.5	NR	oligo-mesotrophic	increase	N/A	no	not reported	Beaver 2013
Lake Sakakawea	USA	47.5	NR	oligo-mesotrophic	decrease	N/A	not reported	yes	Beaver 2013
Lake Sharpe	USA	44	NR	oligo-mesotrophic	increase	N/A	no	not reported	Beaver 2013

Table 2 (continued). Waterbodies included in this literature review that exhibited either a water level increase or decrease. NR = not reported.

Lake or Reservoir Name	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Trophic Status	Did water level increase or decrease?	Maximum water level change (m)	Did phytoplankton increase?	Did cyanobacteria increase?	Study ID
Lewis and Clark Lake	USA	42.9	NR	eu-hypereutrophic	increase	N/A	no	not reported	Beaver 2013
Maggiore	Italy	45.92	8.53	oligo-mesotrophic	increase	3	not reported	yes	Bakker 2016
Maggiore	Italy	45.92	8.53	oligo-mesotrophic	decrease	-3	not reported	yes	Bakker 2016
Miyun	China	NR	NR	not reported	decrease	N/A	not reported	yes	Su 2017
Orós	Brazil	NR	NR	not reported	increase	N/A	yes	not reported	Nunes Carvalho 2022
Orós	Brazil	NR	NR	not reported	decrease	N/A	no	not reported	Nunes Carvalho 2022
Pengxi River	China	30.95	108.64	eu-hypereutrophic	increase	50	no	no	Xiao 2016
Rybinsk Reservoir	Russia	NR	NR	not reported	decrease	N/A	no	not reported	Sakharova 2018
Rybinsk Reservoir	Russia	58.41	38.34	oligo-mesotrophic	increase	N/A	no	no	Mineeva 2021
Rybinsk Reservoir	Russia	58.41	38.34	oligo-mesotrophic	decrease	N/A	yes	yes	Mineeva 2021
Río Tercero Reservoir	Argentina	-32.19	-64.43	oligo-mesotrophic	increase	2.97	no	not reported	Mac Donagh 2009
Río Tercero Reservoir	Argentina	-32.19	-64.43	oligo-mesotrophic	decrease	-2.97	no	not reported	Mac Donagh 2009
Taechung Reservoir	South Korea	36.83	127.83	not reported	increase	N/A	no	not reported	An 2003
Three Gorges Reservoir	China	NR	NR	not reported	increase	-20	no	not reported	Zhou 2022

Table 2 (continued). Waterbodies included in this literature review that exhibited either a water level increase or decrease. NR = not reported.

Lake or Reservoir Name	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Trophic Status	Did water level increase or decrease?	Maximum water level change (m)	Did phytoplankton increase?	Did cyanobacteria increase?	Study ID
Three Gorges Reservoir	China	NR	NR	not reported	decrease	-20	yes	not reported	Zhou 2022
Three Gorges Reservoir (specifically in Xiangxi Bay)	China	30.83	111	eu-hypereutrophic	increase	N/A	no	not reported	Ye 2022
Three Gorges Reservoir (specifically in Xiangxi Bay)	China	30.83	111	eu-hypereutrophic	decrease	N/A	no	not reported	Ye 2022
Tri An	Vietnam	11.21	107.15	eu-hypereutrophic	decrease	-12	yes	yes	Pham 2021
Tri An	Vietnam	11.18	107.16	eu-hypereutrophic	increase	N/A	yes	yes	Pham 2022
Tri An	Vietnam	11.18	107.16	eu-hypereutrophic	decrease	N/A	no	no	Pham 2022
Yale	USA	28.91	-81.74	eu-hypereutrophic	decrease	N/A	not reported	yes	Havens 2019
Zipingpu Reservoir	China	31.02	103.54	not reported	increase	58	yes	not reported	Liao 2024

White and Gray Literature Review

We used a mixed methods approach for our review. To supplement the rapid review methods described above, we also conducted a search for relevant natural resource agency reports that examined water quality in other reservoirs of the Colorado River and/or Rio Grande River Basins. Specifically, we searched for reports that studied water quality responses to drought and water level fluctuation. We searched the National Park Service Integrated Resource Management Applications (IRMA) DataStore (<https://irma.nps.gov/DataStore/>) and the USGS Publications Warehouse (<https://pubs.usgs.gov/>) for the terms “cyanobacteria”, “harmful algal bloom”, “*E. coli*”, and “*Naegleria*”. Given the large number of studies returned with the “*E. coli*” search in the USGS Publications Warehouse, we refined this search to “*E. coli* reservoir”. We also discussed this work with water quality practitioners at the USGS, U.S. Bureau of Reclamation, Southern Nevada Water Authority, and National Park Service for help identifying additional reports or datasets that were relevant to this review. We then chose two case study reservoirs from the desert Southwest, Cochiti and Blue Mesa, where work has been done to characterize the environmental drivers of cyanobacterial blooms (Barton and Johnson 1978, Bauch and Malick 2003).

Statistical Analysis of Studies in the Rapid Literature Review

To determine whether phytoplankton and cyanobacteria exhibited increases or decreases in response to water level changes, we conducted chi-square statistical tests and logistic regressions on the individual waterbody data from the extracted papers.

To perform chi-square tests, each waterbody was first categorized according to whether it exhibited a water level increase or decrease. For waterbodies in which both water level increases and decreases *and* the corresponding phytoplankton or cyanobacterial responses to both increases and decreases in water level were reported, we included the waterbody in both the water level increase and the water level decrease categories. Second, waterbodies were categorized according to whether cyanobacteria or phytoplankton exhibited an increase in response to the water level change. Waterbodies that exhibited decreases in cyanobacteria or phytoplankton, no change, a shift in community structure, other response, or mixed responses in response to water level change were categorized together as “no-increase” responses for chi-square tests due to the limited number of data points.

We then conducted six chi-square tests to determine whether phytoplankton and cyanobacteria exhibited significantly different responses to water level increases and decreases, respectively. First, we conducted a chi-square test to determine if, given an *increase* in water level, there was a significant difference in the observed number of increase and no-increase responses in total phytoplankton. Our null hypothesis for this test was that we should observe the same number of reported increase and no-increase responses of phytoplankton to water level *increase*. Second, we tested whether, given a *decrease* in water level, there was a significant difference in the observed number of increase and no-increase responses in total phytoplankton. Similarly, our null hypothesis for this test was that we should observe an equal number of increase and no-increase responses of phytoplankton to water level *decrease*. Third, we tested whether phytoplankton exhibited significantly different responses to water level increases and decreases. Our null hypothesis for this test was that phytoplankton would exhibit the same number of increase and no-increase responses

across both increases and decreases in water level. Finally, we conducted the same three chi-square tests but for cyanobacteria specifically, resulting in six total chi-square tests.

For purposes of both chi-square analyses and data visualization, we categorized lakes and reservoirs according to trophic status. Trophic status was either assigned based on the trophic status reported by study authors, or according to reported total phosphorus or chlorophyll *a* values following Carlson (1977; Table 3). Two waterbodies were reported as “eu-hypertrophic” and were grouped into the hypereutrophic category. Four waterbodies were identified as meso-eutrophic and were grouped into the eutrophic category. One waterbody was identified as oligo-mesotrophic and was grouped into the mesotrophic category. Because some waterbodies are repeat-sampled, trophic status may be duplicated for some waterbodies. We chose to retain repeat-sampled waterbodies, and thus trophic status, to accurately represent the waterbody instances in the report. While trophic status is displayed in relevant figures, we did not separate lakes and reservoirs according to trophic status when conducting statistical analyses due to data limitations.

Table 3. Trophic state categorization (Carlson 1977).

Trophic state	Phosphorus concentration ($\mu\text{g/L}$)	Chlorophyll concentration ($\mu\text{g/L}$)
Oligotrophic	≤ 12	≤ 2.7
Mesotrophic	> 12 and ≤ 24	> 2.7 and ≤ 7.3
Eutrophic	> 24 and ≤ 70	> 7.3 and ≤ 56
Hypereutrophic	> 70	> 56

For the logistic regression, waterbodies were only included if their maximum depth and a change in water level were reported. We estimated the proportion of water level change for use as a predictor of phytoplankton and cyanobacterial response. This was done by dividing the change in water level of the waterbody by the maximum depth of the waterbody, in which negative values indicate a proportional decline in water level from an initial depth and positive values indicate a proportional increase in water level. Studies that reported both an increase and decrease in water level and a corresponding change in phytoplankton or cyanobacteria were assigned to either an increase or decrease in water level. This assignment was determined based on the original direction of water level change. If the reservoir experienced a drought or drawdown and subsequently a return to normal operating levels, it was assigned as a decrease in water level. If the reservoir experienced flooding that raised water levels beyond normal levels, and then returned to normal levels, it was assigned as an increase in water level. Cyanobacteria and phytoplankton responses were categorized into two groups: an increase in phytoplankton or cyanobacteria (1), or a decrease or no change in phytoplankton or cyanobacteria (0). We then conducted two logistic regressions to determine whether the proportion of water level change could predict the likelihood of phytoplankton or cyanobacterial increases.

Characterization of Studies Analyzed for Rapid Literature Review

Our rapid literature review identified 36 studies that matched our search criteria. Two of those studies focused on pathogens and are detailed below in the Other Pathogens section. Thirty-four studies focused on the impacts of water level fluctuation or selective withdrawal in lakes or reservoirs on chlorophyll, phytoplankton, and/or cyanobacteria. These 34 studies included a total of 49 waterbody instances (Table 2). Some waterbodies were repeat-sampled, leading to a total of 42 distinct lakes and reservoirs included in this review. The reviewed studies covered a broad range of management strategies and concerns, and some studies identified more than one management strategy or concern (see Appendix). Of the 36 studies, 7 studies mentioned drawdown, 22 studies mentioned drought, 9 studies mentioned flooding, and 24 studies mentioned water level fluctuation as management concerns (Figure 2). The reviewed studies also identified drawdown (7), refill (3), flushing (2), and selective withdrawal (3) as management strategies (Figure 3).

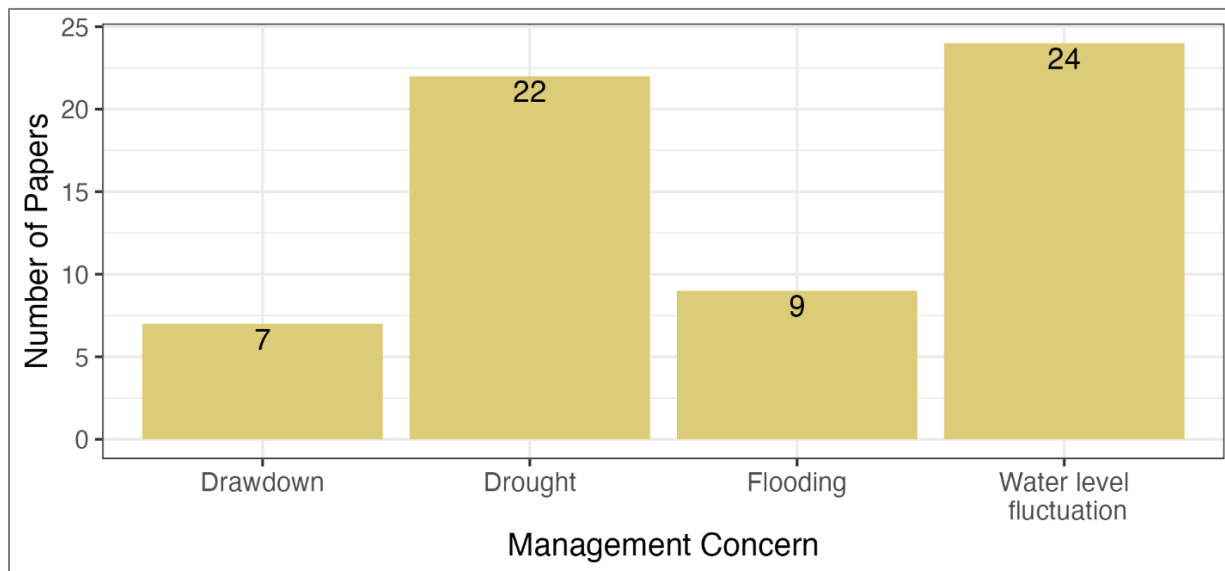


Figure 2. Bar chart showing relevant management concerns contained in the reviewed studies. Not all papers identified a management concern, and some studies identified more than one. ORIGINALLY PRODUCED BY VIRGINIA TECH

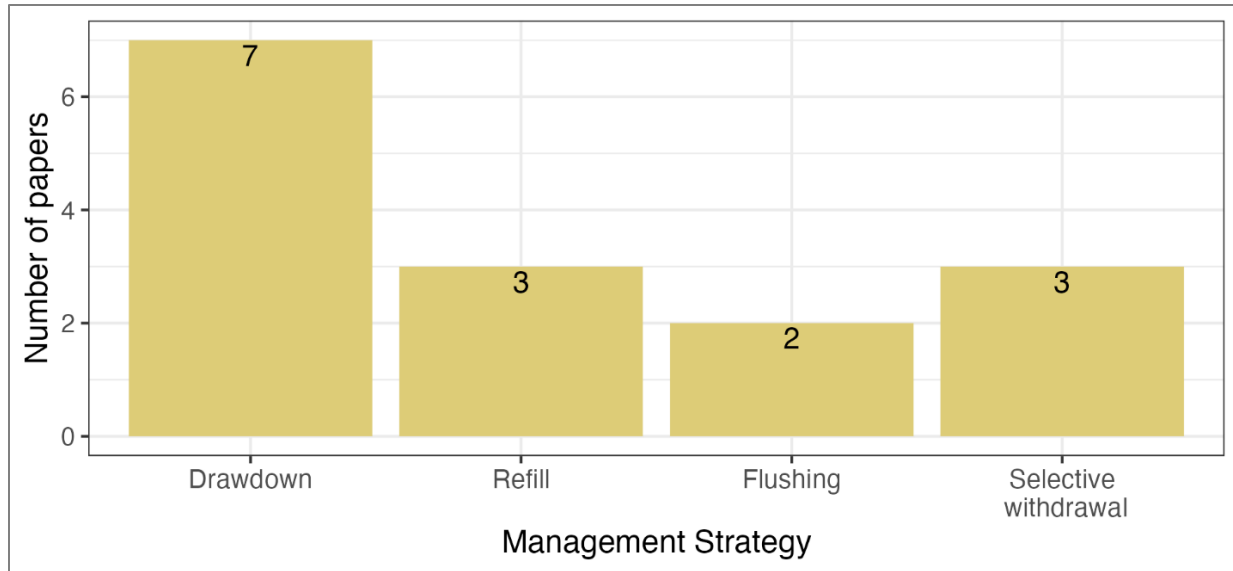


Figure 3. Bar chart showing relevant management strategies contained in the reviewed studies. Not all papers identified a management strategy, and some studies identified more than one strategy.
ORIGINALLY PRODUCED BY VIRGINIA TECH

Waterbodies included in the review were mostly eutrophic (19) or hypereutrophic (6); summed together, these high-nutrient systems represented 69% of the waterbodies that reported trophic state, or 51% of all waterbody instances. Fewer of the waterbodies were mesotrophic (9) or oligotrophic (2) (Figure 4). Six reservoirs were repeat-sampled by multiple papers, with three studies on Three Gorges Reservoir (China) and two studies each on Lake Diefenbaker (Canada), Tri An (Vietnam), Zipingpu (China), Rybinsk (Russia), and Kuibyshev (Russia). Most reservoirs were located in the northern hemisphere, with 15 studies in North America, 8 studies in Europe, 16 studies in Asia, 9 studies in central and South America, and 1 study in Africa (Figure 5).

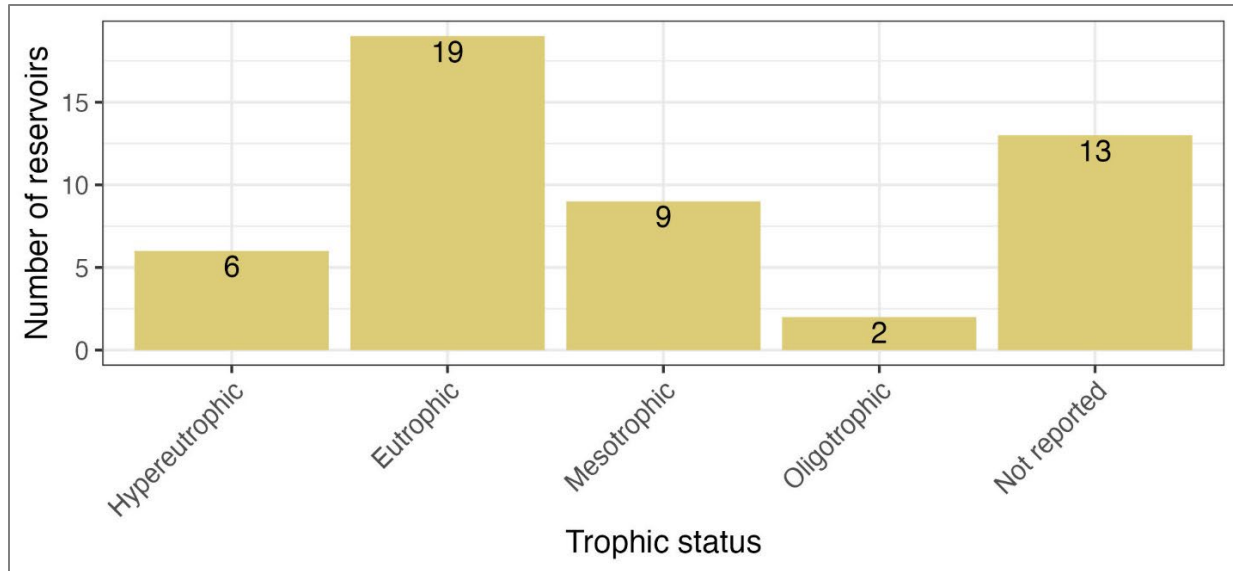


Figure 4. Bar chart showing distribution of trophic status of waterbody sampling events (n = 49) in the reviewed studies. Thirteen waterbodies did not report trophic status and sufficient information was not provided to determine trophic status. ORIGINALLY PRODUCED BY VIRGINIA TECH

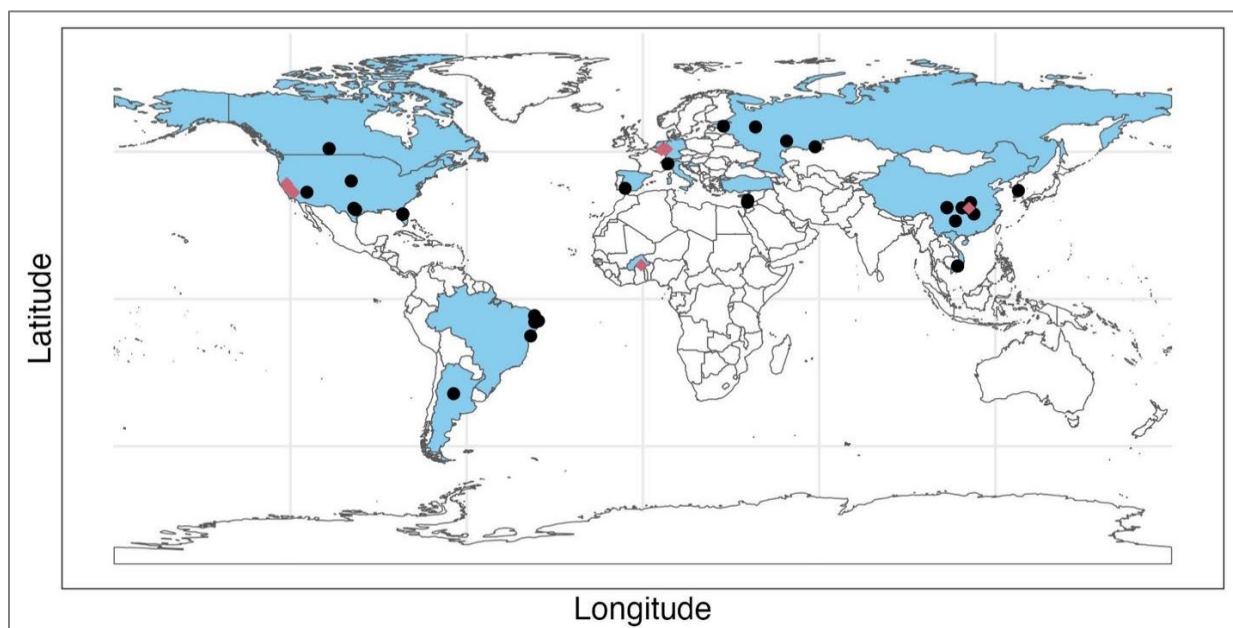


Figure 5. Map of reported waterbody location by country and latitude and longitude (denoted by black dots and pink diamonds). Countries that contain waterbodies included in the review are highlighted in blue. Some studies did not report exact reservoir location, so countries are filled in blue to show the full extent of included waterbodies. Waterbodies with phytoplankton and/or cyanobacterial studies are represented by a black-filled circles and pathogen studies are represented with a pink diamond. Note that because of the close proximity of many sites, the number of points is obfuscated in this projection. ORIGINALLY PRODUCED BY VIRGINIA TECH

Responses to Water Level Changes

Thirty-four of the 36 studies reviewed in this study reported at least one instance of water level change and an associated phytoplankton or cyanobacterial response. In total, there were 47 waterbody instances included in the following analyses. There were 29 waterbodies with responses to water level increases: 25 phytoplankton responses and 14 cyanobacterial responses. These values sum to more than 29 since some studies reported both phytoplankton and cyanobacterial responses. There were 35 waterbodies with responses to water level decreases: 22 phytoplankton responses and 24 cyanobacterial responses. Again, these numbers sum to greater than 35 since some studies reported both phytoplankton and cyanobacterial responses.

Phytoplankton and Cyanobacterial Responses

Findings from the Literature Review

Phytoplankton

About half of waterbodies that experienced decreases in water level exhibited increases in phytoplankton (Figure 6). The other waterbodies that experienced water level decreases exhibited decreases in phytoplankton or responses that were categorized as “other” (Figure 6). Two waterbodies exhibited a shift in community composition to a more cyanobacterial dominated community with decreases in water level, but did not report whether there was an associated increase or decrease in total phytoplankton biomass, phytoplankton biovolume or chlorophyll *a*. An additional two studies reported phytoplankton responses to water level decreases that were categorized as “other”: Ye et al. (2022) and Sakharova and Korneva (2018). Ye et al. (2022) used empirical dynamic modeling to determine the effects of daily water level fluctuation on phytoplankton biomass in Three Gorges Reservoir, China. They found that water level fluctuation can be effective for controlling phytoplankton blooms, and that increases in water level had a more significant effect on reducing phytoplankton than decreases in water level. Sakharova and Korneva (2018) characterized phytoplankton communities in littoral and deep locations across years and water level regimes in Rybinsk Reservoir, Russia, and found that phytoplankton floristic richness increased with decreases in water level. Because neither of these results fit into our categories, they were classified as “other” and ultimately placed into the “no-increase” response to water level change.

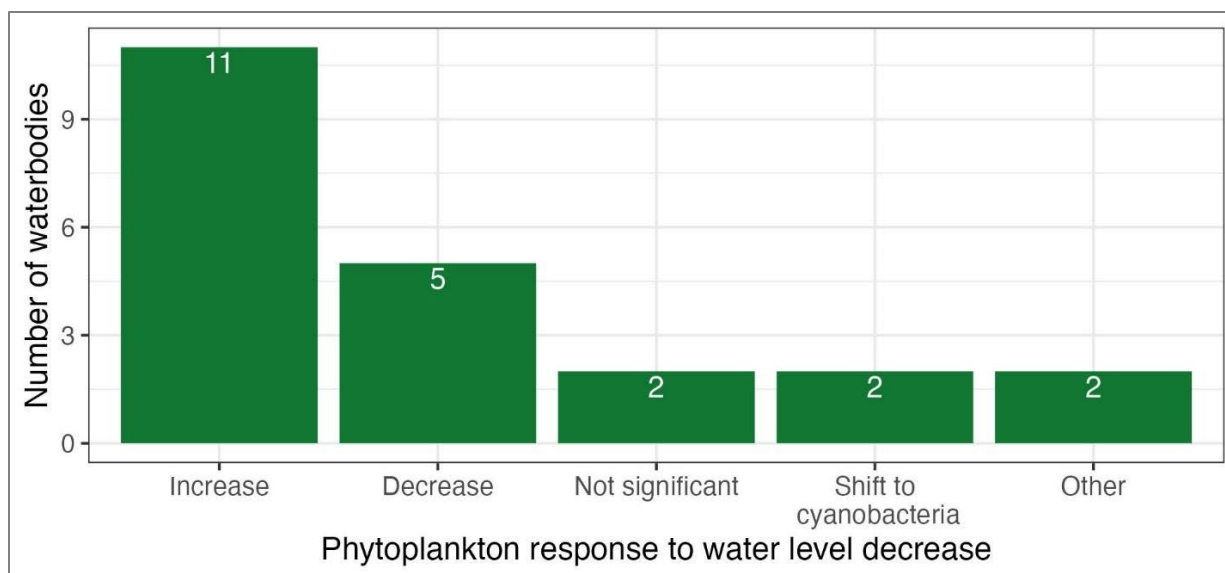


Figure 6. A bar chart showing the number of waterbody instances exhibiting different phytoplankton responses to a decrease in water level. Out of the 47 waterbody instances, 22 reported a phytoplankton response to a water level decrease: Increase (11); Decrease (5); Not significant (2); Shift to cyanobacterial dominated community (2); or Other (2). ORIGINALLY PRODUCED BY VIRGINIA TECH

Generally, waterbodies that experienced increases in water level exhibited decreases in phytoplankton. Out of 25 waterbodies that experienced increases in water level and reported a phytoplankton response, five waterbodies reported increases in phytoplankton, 11 waterbodies reported decreases in phytoplankton, and two waterbodies did not exhibit a significant change (Figure 7). An additional six waterbodies reported a mixed phytoplankton response to water level increases (Beaver 2013). In a series of six reservoirs along the Missouri River, United States, phytoplankton communities were studied during drought, recovery, and flooding (Beaver 2013). Phytoplankton biovolume was generally lowest during the drought and highest during the recovery period in all six reservoirs. Flooding decreased phytoplankton biovolume, but it remained above drought levels.

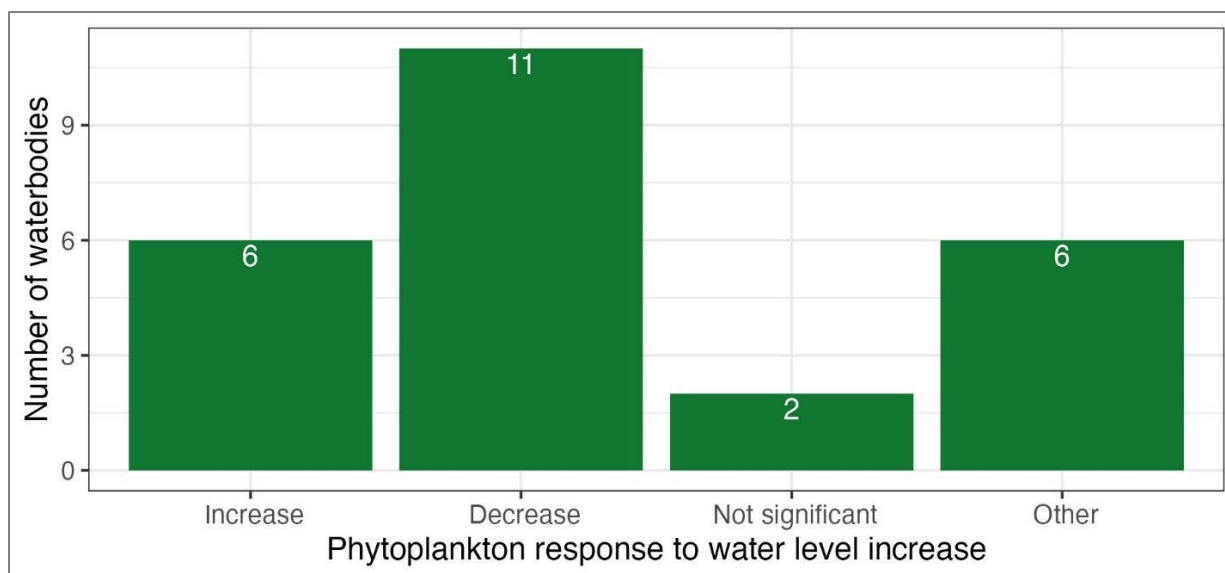


Figure 7. A bar chart showing the number of waterbody instances exhibiting phytoplankton responses to an increase in water level. Out of the 47 total waterbody instances, 19 reported a phytoplankton response to a water level increase: Increase (6); Decrease (11); Not significant (2); and Other (6). ORIGINALLY PRODUCED BY VIRGINIA TECH

Cyanobacteria

Almost unequivocally, waterbodies that reported cyanobacterial responses to decreases in water level experienced increases in cyanobacteria. Twenty-one waterbodies reported increases in cyanobacteria in response to decreases in water level. Two waterbodies reported decreases in cyanobacteria in response to decreases in water level, and one waterbody reported no significant differences in cyanobacteria in response to water level decreases (Figure 8).

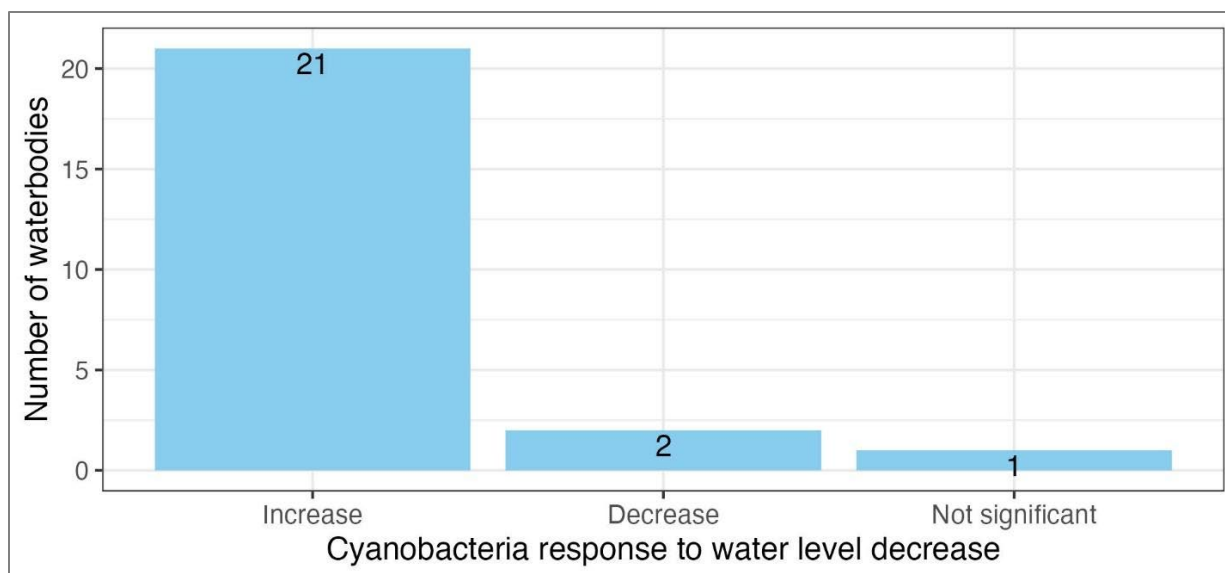


Figure 8. Bar chart showing cyanobacterial responses to decreases in water level. Out of 47 waterbody instances, 24 reported a cyanobacterial response to water level decreases: Increase (21); Decrease (2); or Not significant (1). ORIGINALLY PRODUCED BY VIRGINIA TECH

In contrast, cyanobacterial responses to increases in water level were mixed, with seven waterbodies reporting an increase and seven studies reporting a decrease in cyanobacteria in response to water level increases (Figure 9). Our findings were generally consistent with a study of subtropical reservoirs that linked declines in reservoir water level to increased dominance of cyanobacteria (Yang et al. 2016).

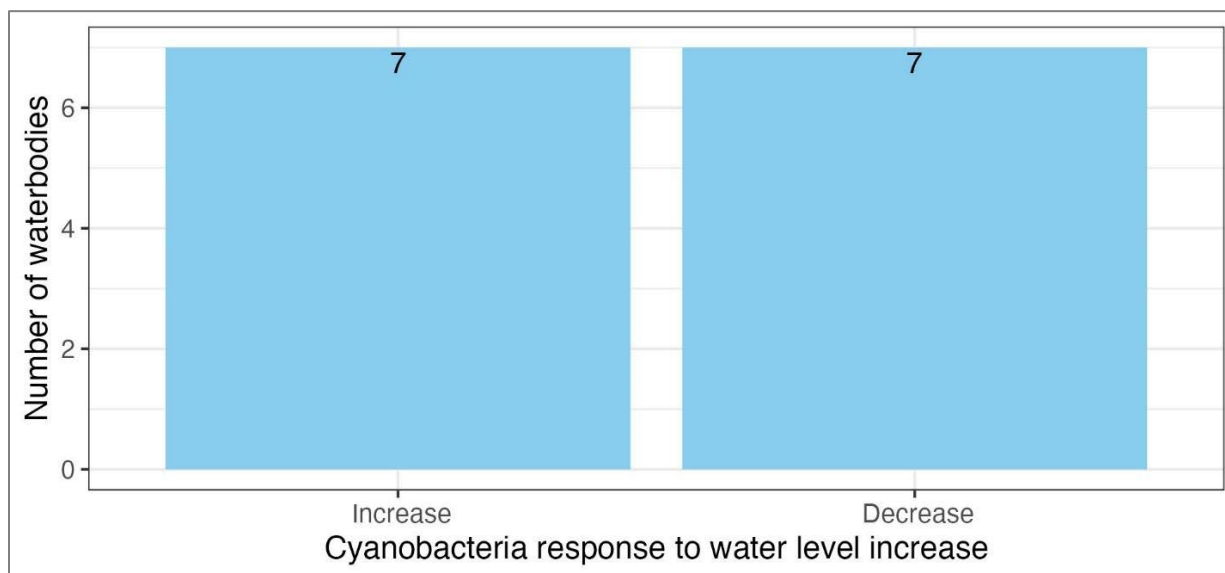


Figure 9. Bar chart showing cyanobacterial response to increases in water level. Out of 47 waterbody instances, 14 reported a cyanobacterial response to water level increases: Increase (7); or Decrease (7). ORIGINALLY PRODUCED BY VIRGINIA TECH

Statistical Analyses

Chi-square Tests

Phytoplankton

Phytoplankton were significantly more likely to exhibit a “no-increase” response when water levels increased ($\chi^2(1, N = 25) = 6.76, p = 0.009$; Figure 10). Of 25 reported instances of phytoplankton responses to water level increases, 19 exhibited “no-increase” responses after an increase in water level. In contrast, there were an equal number of reported increase and no-increase responses of phytoplankton to water level decrease ($n = 11$ for each; $\chi^2(1, N = 22) = 0, p = 1$; Figure 10). While more studies reported increases of phytoplankton in response to water level decreases than water level increases, phytoplankton did not exhibit a significantly different response to increases vs. decreases in water level according to chi-square tests ($\chi^2(1, N = 47) = 2.39, p = 0.12$; Figure 10). In total, we identified 11 instances of reported increases in phytoplankton following water level decreases, and six instances of reported increases in phytoplankton following water level increases. In contrast, there were 30 reported instances of water level increases or decreases that led to phytoplankton decreases, no change, or shifts in phytoplankton community structure. Overall, we identified a similar number of reported instances of water level increases and decreases ($n = 25$ reported increases vs. $n = 22$ reported decreases) in our dataset.

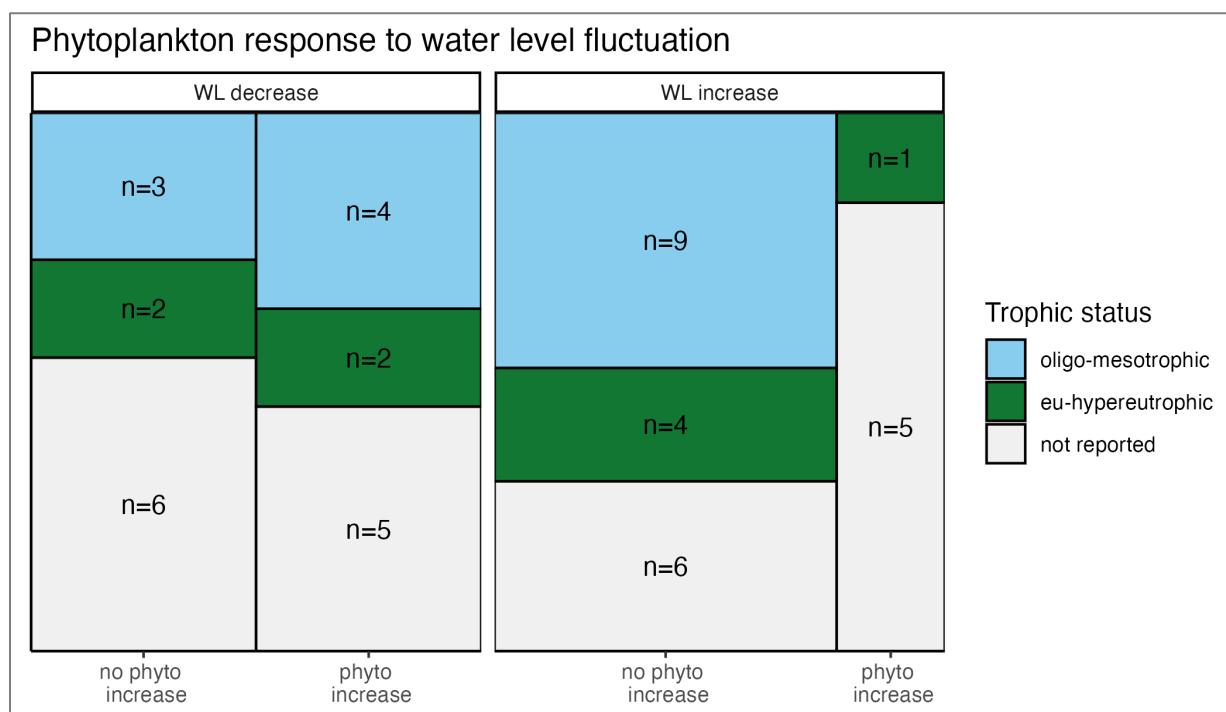


Figure 10. Analysis of phytoplankton responses to waterbody water level fluctuation, as reported in the literature. Waterbody trophic status was either reported by study authors or determined following Carlson (1977) using reported values of total phosphorus and chlorophyll *a*. Text inlaid on the figure reports the number of data points falling into each category out of a total of $n=47$ reported instances of phytoplankton responses to water level changes. ORIGINALLY PRODUCED BY VIRGINIA TECH

Cyanobacteria

Cyanobacteria were significantly more likely to increase in response to water level decreases ($\chi^2(1, N = 24) = 13.5, p = 0.0002$; Figure 11). Of 24 reported instances of cyanobacterial responses to water level decreases, 21 reported increases in cyanobacteria after a decrease in water level. In contrast, there were an equal number of reported increase and no-increase responses of cyanobacteria to water level decrease ($n = 7$ for each; $\chi^2(1, N = 14) = 0, p = 1$; Figure 9). In addition, cyanobacteria exhibited a significantly different response to increases vs. decreases in water level according to chi-square tests ($\chi^2(1, N = 38) = 4.62, p = 0.03$; Figure 11); specifically, cyanobacteria were more likely to increase after water level decreases than water level increases. However, due to an imbalance in the number of reported instances of water level increases and decreases ($n = 14$ reported increases vs. $n = 24$ reported decreases), chi-square test results should be interpreted carefully. In total, we identified 21 instances of reported increases in cyanobacteria following water level decreases, and seven instances of reported increases in cyanobacteria following water level increases. In contrast, there were 10 reported instances of water level increases or decreases that led to cyanobacterial decreases, no change, or shifts in cyanobacterial community structure.

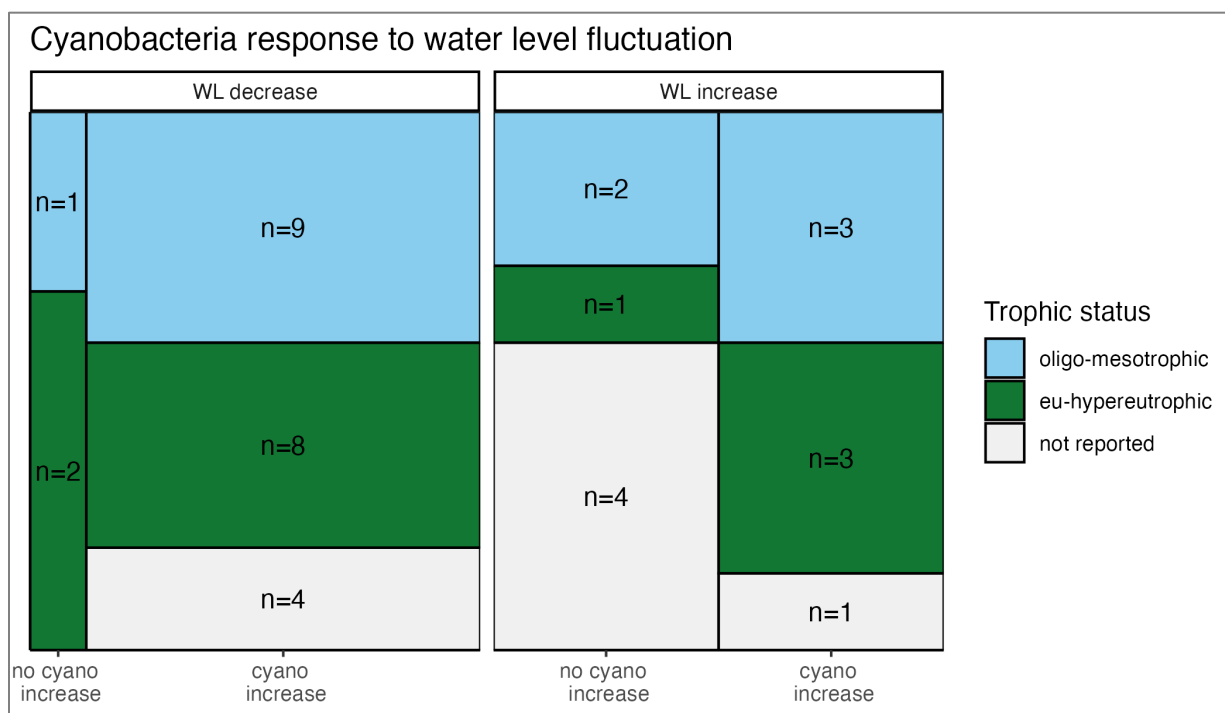


Figure 11. Analysis of cyanobacterial responses to waterbody water level fluctuation as reported in the literature. Waterbody trophic status was either reported by study authors or determined following Carlson (1977) using reported values of total phosphorus and chlorophyll *a*. Text inlaid on the figure reports the number of data points falling into each category out of a total of $n=38$ reported instances of cyanobacterial responses to water level changes. ORIGINALLY PRODUCED BY VIRGINIA TECH

Logistic Regression

Phytoplankton were more likely to increase in response to water level decreases. Of the 14 waterbody instances for which we could calculate a proportional water level change that had a

phytoplankton response and reported both maximum depth and measured water level change, 8 reported increases in phytoplankton, and 6 reported decreases in phytoplankton. This result is not statistically significant at $\alpha = 0.05$ ($p = 0.066$; Figure 12); however, we note that it is significant at $\alpha = 0.1$. This finding aligns with the chi-square test that found phytoplankton were significantly less likely to increase in response to water level increases, so we interpret this as a potentially meaningful result.

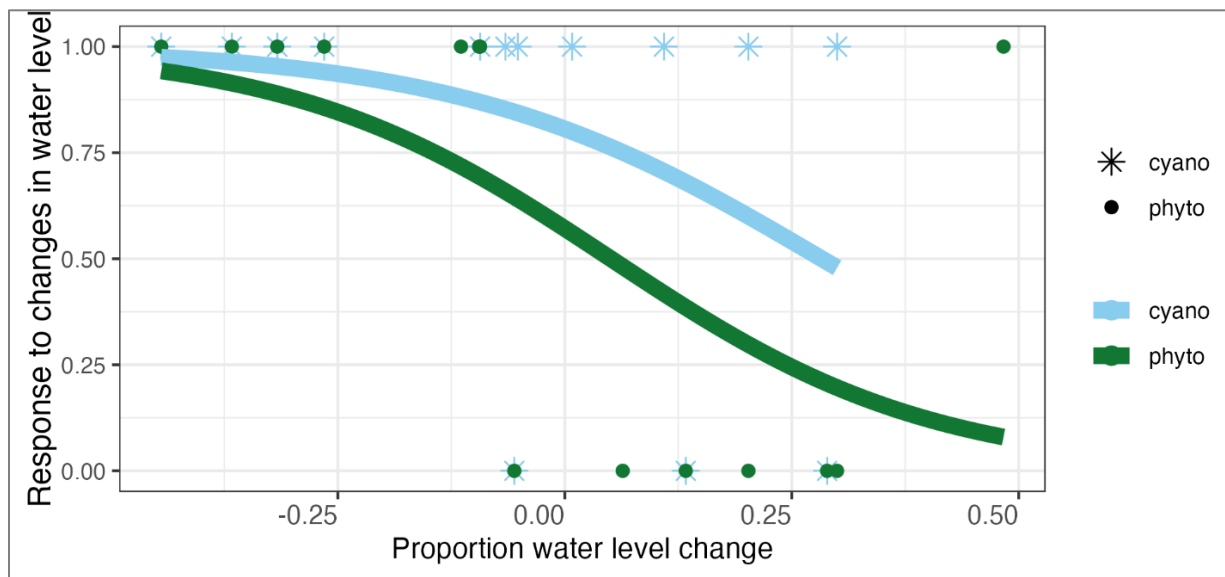


Figure 12. Two logistic regressions show the likelihood that cyanobacteria and phytoplankton will increase due to water level change. On the x axis, a negative proportional water level change indicates a decline in water level, and vice versa. On the y axis, a value of one indicates an increase in phytoplankton and a value of zero indicates either a decrease, a non-significant change, or some other response. Neither of the logistic regressions were significant at $\alpha = 0.05$ (phytoplankton, $p = 0.066$, $n=14$; cyanobacteria, $p = 0.195$, $n=14$). We could not estimate proportional water level change for all reviewed studies as this required data on both the maximum depth of the waterbody and number of meters the waterbody increased or decreased. ORIGINALLY PRODUCED BY VIRGINIA TECH

According to the logistic regression analysis, cyanobacteria were not significantly more likely to experience increases in proportional declines in water level ($p = 0.20$; Figure 12). Of the 14 waterbody instances with a cyanobacterial response to water level change and both a maximum depth and a reported change in water level, 11 reported an increase in cyanobacteria and 3 reported a decrease in cyanobacteria.

Characterization of Studies Identified by Agency Search

Our search of the NPS IRMA and USGS Publications Warehouse yielded seven studies within the Colorado or Rio Grande River Basins that measured phytoplankton, cyanobacteria, *E. coli*, or *N. fowleri* on a reservoir. We focus our case studies on reservoirs studied in two of these papers (Cochiti Reservoir in Barton and Johnson 1978, and Blue Mesa Reservoir in Bauch and Malick 2003). The Blue Mesa case study also draws from more recent ongoing work to characterize algal blooms. We chose these two reservoirs as the best representative studies of reservoirs within the southwest United

States that fit our literature review criteria and are relevant to Lake Powell and Lake Mead Reservoirs.

Of the five additional studies, two studies were conducted on Lake Powell, but neither was directly focused on phytoplankton, cyanobacteria, or pathogens. One describes a two-year water quality sampling program on Lake Powell and reports on nutrients, major ions, volatile organic compounds, organic wastewater compounds and bacteria including *E. coli*, among other variables (Hart et al. 2005). The second characterizes mercury dynamics in Lake Powell and compares conditions in the tributaries to those in the main channel of the reservoir, which included measurements of phytoplankton concentrations (Naftz et al. 2019). One study focused on *N. fowleri* (Detterline and Wilhelm 1991) and is summarized in the pathogens section below. Another study describes water quality measurements made in the Upper Gunnison Watershed, including chlorophyll *a* measurements from Blue Mesa Reservoir (Gurdak et al. 2002). Lastly, a survey of water quality on 56 Colorado reservoirs was conducted during the summer/fall of 1973, 1974, and 1975 and includes phytoplankton cell concentrations (Britton and Wentz 1980).

Case Studies

Cochiti Reservoir (Sandoval County, New Mexico)

Cochiti Reservoir is an impoundment on the Santa Fe River in the Rio Grande River Basin. The dam was built in 1975 and is managed by the Army Corps of Engineers. A study was conducted in 1976 and 1977 to examine patterns in limnological conditions, nutrients, nitrogen fixation, phytoplankton community, bacterial counts (fecal coliform and *Streptococcus*), and cyanobacterial toxicity (Barton and Johnson 1978). The reservoir underwent 5% fluctuations in storage volume during the study.

In 1976, shortly after Cochiti Reservoir was completed, it experienced large cyanobacterial blooms dominated by toxin-producing *Aphanizomenon flos-aquae* with smaller blooms occurring in 1977 (Barton and Johnson 1978). The blooms were of sufficient magnitude to be a concern for livestock toxicity (and for future plans for municipal use), so animal toxicity studies were employed during peak bloom periods. The phytoplankton were found to be highly toxic to laboratory white mice (Barton and Johnson 1978). The reduced bloom size in 1977 corresponded with generally lower total nitrogen and phosphorus concentrations in the reservoir. Cochiti Reservoir was characterized as eutrophic in the summer of 1976 and mesotrophic in 1977 (Barton and Johnson 1978). There was no mention of water level as a potential control on blooms in the study.

Fecal pollution was relatively low with fecal coliforms and fecal *Streptococci* being most numerous near the inlet and the boat dock, where recreational activity was greatest (Barton and Johnson 1978).

Blue Mesa Reservoir (Gunnison County, Colorado)

Blue Mesa Reservoir is an impoundment on the Gunnison River in the Upper Colorado River Basin and is part of the Aspinall Unit managed by the Bureau of Reclamation (BOR). The surrounding area and recreation on the reservoir are managed by the National Park Service (NPS) as part of Curecanti National Recreation Area (NRA). NPS conducts routine water quality monitoring that is part of an

ongoing assessment of cyanobacterial blooms in Blue Mesa Reservoir (Weissinger and Gibney 2019; King et al. 2024).

Multiple cyanobacterial species have consistently been documented in Blue Mesa since 1975, with *Aphanizomenon* being the most prevalent (Cudlip et al 1987; Bauch and Malick 2003). Blue Mesa has historically been mesotrophic in the upstream (more shallow) areas of the reservoir and oligotrophic in the downstream (profundal) areas (USEPA 1977, Bauch and Malick 2003). While the trophic-state index values (calculated using methods from Carlson, 1977) only periodically exceeded 50 in 1999 (Bauch and Malick 2003), by 2022 they were consistently exceeding 50 and even exceeded 60, classifying the upstream areas of the reservoir as eutrophic (data from the USGS National Water Information System; U.S. Geological Survey 2023). In 2018, the NPS anecdotally started noticing larger cyanobacterial blooms on the reservoir and began testing for cyanotoxins. Water samples collected in September 2018 were sent to the Colorado Department of Public Health and Environment (CDPHE) lab for liquid chromatography with tandem mass spectrometry (LC-MSMS) analysis and the microcystin-LR concentrations were found to exceed the state threshold for total microcystins of 8 µg/L (CDPHE, 2020). Over the last six years from 2018–2023, cyanotoxins have been detected every year, with the state threshold exceeded in four of those years. During the two years when the state threshold was not exceeded, the reservoir started the calendar year at an elevation of 7,437–7,446 ft (249–293 kaf) and peaked at or near full pool elevation of 7,512–7,519 ft (767–827 kaf) in July, which represents the highest reservoir elevations across the six years.

In 2022, cyanotoxins reached their highest recorded levels with enzyme-linked immunosorbent assay (ELISA) analysis results of 412 µg/L for total microcystins. The 2022 water year started off with record low water levels at Blue Mesa due to the Drought Release Operations Agreement that was put in place in 2019, which moves water from upstream reservoirs down to Lake Powell to protect critical elevations at Lake Powell (Colorado River Drought Contingency Plan Authorization Act. Pub. L. No. 116–14, 133 Stat. 850 (2019)). Blue Mesa Reservoir fell to 7,429 ft (210 kaf) in November 2021 and only recovered to peak at 7,463 ft (395 kaf) after spring runoff in July 2022.

Other Pathogens

Our formal literature search terms included “*naegleria*”, “*N. fowleri*”, “*Naegleria fowleri*”, “*E. coli*”, and “*Escherichia coli*”, but we only identified five papers that reported on *E. coli* and did not identify any papers addressing *N. fowleri* dynamics in reservoirs.

Two of the five *E. coli* studies were conducted in Three Gorges Reservoir, China (Zhao et al. 2016; Xiang et al. 2021), where fecal coliform has been identified as a key pollutant affecting the reservoir. *E. coli* generally exceeded water quality objectives established by the Chinese Ministry of Environmental Protection (10,000 counts per liter) at sites located in densely populated areas (with municipal sewage the likely culprit; Zhao et al. 2016). One of the papers compared *E. coli* during low and high water level periods and found the highest counts during the low water level period of each year, as the reservoir typically fluctuates about 30 m each year from low water in the wet season to high water in the dry season (Xiang et al. 2021). Another study examined tributary microbial loading to three German drinking water reservoirs and found that rainfall events and extreme runoff events

were responsible for a substantial share of total microbial loading which included *E. coli*, coliform, fecal *Streptococcus*, and *Clostridium perfringens* (Kistemann et al. 2002). In a reservoir in Burkina Faso, *E. coli* (and incidents of diarrheal disease in the region) were positively correlated with monsoonal precipitation and suspended particulate matter concentrations (Robert et al. 2021). Finally, one study quantified *E. coli* and *Salmonella* in six irrigation reservoirs in California, United States experiencing drought, sampling monthly across vertical and horizontal profiles for five months total. The study did not find any statistically significant relationships between the pathogens and water temperature or depth strata (Partyka et al. 2018). All in all, the studies do not conclusively link pathogen outbreaks directly to low water levels. Instead, studies related pathogens to rainfall events (Kistemann et al. 2002, Robert et al. 2021) and population density (Zhao et al. 2016).

Our agency report search returned one study of *N. fowleri*, a survey of thermotolerant amoebas in federal recreational freshwaters (Detterline and Wilhelm 1991). The survey was conducted in 1987 and consisted of 59 water samples collected across 43 management units of the Fish and Wildlife Service, National Park Service, and National Forest Service. The survey included two sites on Lake Powell (Bullfrog and Lone Rock areas), one site on Lake Mead, and three other Utah sites (one in Zion National Park and two in Fish Springs National Wildlife Refuge). *N. fowleri* was not detected at any of the desert southwest sites, but other thermotolerant amoeba species were found at Lake Mead (*Acanthamoeba* sp., 1 per 500 mL), at Zion National Park (*Vahlkamfia* sp., 1 per 500 mL), and at Fish Springs National Wildlife Refuge (*Naegleria lovaniensis* and *Vahlkamfia* sp.). In total, *N. fowleri* was detected at six sites nationally. The report found that *N. fowleri* was most likely to be found in habitats that had been recently disturbed and where conditions are tolerable for the amoeba (defined by waterbody temperature, trophic status, and iron concentration; Detterline and Wilhelm 1991). A review of 36 papers that examined abiotic or biotic factors influencing *N. fowleri* found that the species has a wide pH range, low salinity tolerance, and thermophilic preference (Stahl and Olson 2021). While its thermal optimum is likely around 40°C, the review points out that *N. fowleri* has been detected in environmental water samples from 16°C to 47°C. Cysts can even tolerate freezing conditions, emerging from aquatic sediments when conditions are again favorable, suggesting capacity for sustained presence at sites where *N. fowleri* has previously been detected (Stahl and Olson 2021). Some have proposed that *N. fowleri* thrives after environmental disturbance and in human constructed environments, but more work is needed to understand the underlying mechanisms controlling its distribution (Stahl and Olson 2021).

Some other pathogens and diseases not included in this review include norovirus, *Salmonella*, schistosomiasis, *Giardia*, and parasites of fish and macroinvertebrates. Norovirus outbreaks have occurred regularly among rafters in Grand Canyon and have been linked to food contamination (Malek et al. 2009) or to asymptomatic passengers as carriers (Magill-Collins et al. 2015), but direct contamination of Colorado River water has not been implicated.

Highlighted Studies of Particular Relevance to Lake Powell and Lake Mead

One peer-reviewed study identified in our rapid review search was conducted on Lake Mead (Beaver et al. 2018). We consider this a particularly relevant paper given that it was conducted on one of our focal reservoirs of interest. The study aimed to characterize the response of phytoplankton and zooplankton communities to both linear and dynamic environmental changes across a 9-year period and found that a particularly warm winter with low snowpack preceded a large summer bloom of toxic cyanobacteria (*Microcystis aeruginosa*) in Las Vegas Bay (Beaver et al. 2018). A photo from this 2015 bloom is pictured on the cover of this cooperator report. An article published after we conducted our rapid review analyzed 17 years of phytoplankton community data in Lake Mead and reports relatively stable cyanobacterial abundance despite declining water levels, with the exception of shallow regions of the reservoir (Van Der Nagel et al. 2024).

Two other peer-reviewed studies in our search seem particularly relevant given their focus on large magnitude water level increases (Pan et al. 2018) and decreases (Mendes et al. 2022). In Danjiangkou Reservoir, China, a dam retrofitting project resulted in a 40% increase in storage capacity, resulting in the flooding of previously un-flooded land (Pan et al. 2018). Such a large refill is a somewhat relevant analogy to complete refill of Lake Powell or Lake Mead (where 30+ years have passed since higher elevations in the reservoirs have been inundated). Inundation led to a decrease in phytoplankton biomass, but a relative increase in cyanobacteria, including *Lyngbya sp.*, a group that can produce potent lethal neurotoxins (Pan et al. 2018). In three semi-arid Brazilian reservoirs, patterns in water quality, chlorophyll *a*, and phytoplankton community structure were examined during large drought-related reductions in water volume, wherein reservoirs experienced 48–85% declines in water volume (Mendes et al. 2022). These declines were associated with increased biomass of heterocystous filamentous cyanobacteria in two of the three reservoirs, but not in the third (Mendes et al. 2022). The reservoir with no elevated cyanobacteria during low water level conditions was also the only one of the three to experience no change in trophic status with water decline, and the only one to experience clearer water conditions during low water (Mendes et al. 2022).

Two additional studies that emerged from the rapid review focused on oligotrophic waterbodies, which are particularly relevant to Lake Powell, given its oligotrophic (phosphorus limited) trophic status. One of the two oligotrophic systems, Lago Maggiore (Italy), was also the deepest of the $n=42$ waterbodies at 372 m (see review by Bakker and Hilt 2016 and primary study by Callieri et al. 2014). On Maggiore, drying and rewetting of lake shore sediments led to higher phosphorus release from sediments and increasing blooms of the toxin-producing cyanobacterial species *Dolichospermum lemmermannii* (Callieri et al. 2014). The second oligotrophic waterbody was Lake Austin, a municipal reservoir in Texas, United States (Bellinger et al. 2018). The study found that drought-induced discharge reductions, which lowered water level, created conditions more conducive to cyanobacterial blooms, with 2- to 8-fold increases in water residence time during drought. Phytoplankton blooms increased from 1.1% of growing season days during high discharge years to

30% of the growing season days exhibiting blooms during low discharge years, and the probability of a cyanobacterial bloom doubled during drought-related low discharge (Bellinger et al. 2018).

Management and Monitoring Goals

Water managers in the Colorado River Basin are currently identifying broad ranging alternatives for how water is allocated and stored through the Post-2026 EIS process (U.S. Bureau of Reclamation, 2023). The National Park Service (NPS) mission at Lake Powell and Lake Mead National Recreation Areas is to “preserve unimpaired the natural and cultural resources and values of the National Park System for the enjoyment, education, and inspiration of this and future generations” (National Park Service Organic Act, Pub. L. No. 64-235, 39 Stat. 535 (1916)). In this section we provide three goals that are relevant to achieving this mission: 1) anticipate specific aspects of reservoir water management that may degrade water quality, 2) develop prediction and/or early detection capacity for water quality events that pose a risk to human and/or pet health, and 3) develop infrastructure that prevents human use from degrading reservoir water quality.

The literature review in this report was designed to address goal one, to anticipate how water level fluctuations may degrade water quality. The number of studies that could be included in our analysis was limited by the schedule of the Post-2026 EIS process (U.S. Bureau of Reclamation 2023). Thus, expanding the review to include more studies would increase the statistical power of future analyses. Expanding the review would also enable researchers to explore how water level fluctuations affect cyanobacterial dominance and phytoplankton communities overall. Additional analyses of existing data from Lake Powell and Lake Mead could improve understanding of how phytoplankton communities have responded to water level fluctuations and other concomitant water quality changes (such as establishment of Quagga mussels). Both Lake Powell and Lake Mead have publicly available data on phytoplankton species composition and abundance at multiple sampling stations (Deemer et al. 2023, Van Der Nagel et al. 2024). To that end, a cohort of postdoctoral scholars at the Southern Nevada Water Authority are supporting a variety of relevant water quality investigations on Lake Mead (D. Hannoun, Southern Nevada Water Authority, oral communication, September 24, 2024), but less work is ongoing at Lake Powell.

Given our finding that cyanobacteria generally increase in response to water level declines, developing early detection capacity for cyanobacterial toxins, especially given the ongoing drought and associated potential for large water level declines in both reservoirs (Udall and Overpeck 2017), would support goal two. Monitoring for cyanobacterial toxins is already ongoing in Lake Mead, but there is no current toxin monitoring implemented in Lake Powell. If the goal is to reduce human exposure to cyanobacterial toxins, monitoring could be focused in marinas and other heavily recreated areas of the reservoir. In the longer term, developing capacity for near-term forecasting of cyanobacterial and other phytoplankton blooms would support goal two. This could include developing relationships between measurements of phytoplankton pigments and satellite reflectance data and building predictive reservoir models that forecast phytoplankton and cyanobacterial abundance.

An analysis of how recreation patterns are changing in response to changing water levels on both reservoirs could support goal three. If such an analysis were to identify areas of the lake that were experiencing heavy recreational use under lower water levels, these areas could then be equipped

with access to toilets and/or could be permitted to decrease use levels to reduce the risk of *E. coli* and other pathogens in the water, for example.

Limitations of this Analysis

Our mixed methods literature review generally found a higher likelihood of increases in cyanobacteria during water level declines. The logistic regression analysis suggests that the likelihood of cyanobacterial increases is positively related to the magnitude of the water level change, however, we currently lack the statistical power to determine the significance of this effect and to identify a threshold water level change magnitude for which cyanobacterial increases are most likely. Thus, the results of the logistic regression should be interpreted with caution. Consequently, including additional reservoirs in these analyses would improve our statistical power in the chi-square analyses. Another limitation of our analysis is that we did not quantitatively distinguish between a cyanobacterial increase and a “bloom”, as this term has many different meanings within the limnological research community (e.g., Isles and Pomati 2021). Additionally, because studies are less likely to report statistically insignificant results, it is possible that our results have a confirmation bias. Despite these limitations, we note that this review is the first synthesis of peer-reviewed studies on the response of phytoplankton and cyanobacteria to water level change in deep lakes and reservoirs and provides valuable insight into how reservoirs in the Colorado River Basin and other deep reservoirs experiencing drought-related water level fluctuations may respond to variable water level conditions.

We did not find enough papers in our literature review to characterize the effects of water level drawdown on *N. fowleri* and *E. coli*. This may be due to a multitude of factors, including that water level change is unlikely to be the driving factor controlling *N. fowleri* and *E. coli*. We did identify relevant literature that addressed *N. fowleri* and *E. coli*, which motivates future work.

Future Directions

While many of the studies contained in this literature review did not quantify the overall volumetric changes in waterbody capacity, this information could emerge from more in-depth follow-up work. Including additional studies would allow us to increase the sample size for our logistic regression analysis (Figure 12), with the goal of identifying a quantitative threshold for proportional water volume decline under which increased cyanobacterial prevalence is more likely. Additional studies would also allow exploration of questions about the impact of reservoir size, trophic state, and depth on phytoplankton and cyanobacteria.

Similarly, this review highlights the lack of phytoplankton and cyanobacterial studies that investigate the effects of drought and water level fluctuation in oligotrophic waterbodies. While the dominant research paradigm in limnology links cyanobacterial blooms to lakes with eutrophic conditions, recent work suggests a growing prevalence of cyanobacterial blooms in oligotrophic systems (reviewed by Reinl et al. 2021), especially those that have quagga or zebra (*D. polymorpha*) mussels present. Our review underscores the need for more research that examines how water level change affects phytoplankton community structure specifically in oligotrophic reservoirs.

Conclusion

Reservoirs worldwide are under pressure from increased water consumption and a changing climate. In this review, we characterized water level fluctuations and associated risks of increases in phytoplankton, cyanobacteria, and pathogens, including *E. coli* and *Naegleria* spp., based on a literature review of both peer-reviewed and relevant white and gray literature. We note that we did not find a sufficient number of studies on *E. coli* and *Naegleria* spp. to conduct statistical analyses.

We found that cyanobacteria are significantly more likely to increase in response to decreases in water level and that phytoplankton are significantly less likely to increase in response to increases in water level. In addition, we found that cyanobacteria exhibited a significantly different response to increases vs. decreases in water level and were more likely to increase after water level decreases than water level increases, though these results should be interpreted carefully due to limited data. We did not detect significant differences in phytoplankton responses to increases vs. decreases in water level. Many studies did not report the amount of water level change, and only two waterbodies were oligotrophic, highlighting future research needs.

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Appendix

This appendix includes Table 4 which provides more detail on the individual studies included in this review.

Table 4. A description of each of the studies included in this review, the number of waterbodies in each study, reported management strategies or concerns, and reported response variables.

Study	Aim of study	Number of waterbodies	Management strategy or concern	Reported response variable(s)
Abirhire et al. 2019	assess effect of hydrological drought on chlorophyll-a using 31 years of hydrologic data and remotely sensed chlorophyll-a	1	drought	filtered chlorophyll ($\mu\text{g/L}$)
Abirhire et al. 2023	investigate how changes in flow (high flow vs. low flow years) affect major phytoplankton groups and cyanobacterial community in a river-reservoir using a 9-year timeseries	1	increased water extraction	phytoplankton microscopy
An et al. 2003	analyze how hydrological fluctuations (monsoons) influence water quality of a reservoir over a two-year period	1	flooding	filtered chlorophyll ($\mu\text{g/L}$)
Bakker & Hilt 2016	review of 12 case studies reporting water level fluctuations and effects on cyanobacteria, 3 fit our review criteria	3	water level fluctuation	N/A (review)
Beaver et al. 2013	assess drought and flood effects on phytoplankton community dynamics in six reservoirs of the middle Missouri River	6	drought; flooding	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Beaver et al. 2018	characterize the response of phytoplankton and zooplankton communities to both linear and dynamic environmental changes across a 9 year time frame.	1	drought; drawdown	phytoplankton microscopy; cyanobacterial toxins
Bellinger et al. 2018	analyze effects of changing residence times (hydraulic pulsing rates) on ecosystem biophysicochemistry (cyanobacteria blooms, deep water hypoxia, submerged aquatic vegetation)	1	drought; drawdown; hydraulic flushing	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Camara et al. 2015	analyze structure and function of the phytoplankton community in a Brazilian reservoir during La Niña	1	flooding	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Dzhaiani 2020	examine interannual changes in phytoplankton as they relate to hydrodynamics	1	water level fluctuation	phytoplankton microscopy

Table 4 (continued). A description of each of the studies included in this review, the number of waterbodies in each study, reported management strategies or concerns, and reported response variables.

Study	Aim of study	Number of waterbodies	Management strategy or concern	Reported response variable(s)
Fadel et al. 2015	understand the processes controlling phytoplankton succession and other ecosystem variables in a reservoir with high water level fluctuation	1	water level fluctuation	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Gómez et al. 2023	investigate the probability of cyanoHABs in a subtropical reservoir under drought	1	drought	phytoplankton microscopy
Havens et al. 2019	assess hydrologic factors controlling dynamics of cyanobacteria in shallow lakes in Florida	3	drought; water level fluctuation	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Hoyer et al. 2009	characterize how changes in outflow influence phytoplankton community composition in a reservoir	1	drought; selective withdrawal	phytoplankton microscopy
Huang et al. 2023	assess the effect of flushing (reducing water residence time to 3 days) on the growth of cyanobacteria and occurrence of blooms	1	hydraulic flushing	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Khaliullina et al. 2009	analyze seasonal and interannual variation in the phytoplankton community in connection with seasonal water level changes using a long-term dataset	1	water level fluctuation	phytoplankton microscopy
Khaliullina & Khaliullin 2022	study the influence of abiotic factors on seasonal phytoplankton dynamics	1	drawdown	phytoplankton microscopy
Kistemann et al. 2002	assess microbial load to drinking water reservoirs during extreme rainfall and runoff events	3	flooding	<i>E. coli</i>
Li et al. 2018	evaluate the influence of water level fluctuations (flood), temperature, stratification, and nutrients on the development of phytoplankton and cyanobacteria	1	water level fluctuation; flooding	phytoplankton microscopy
Liao et al. 2024	investigate the impact of water level operations on algal blooms in a canyon reservoir	1	water level fluctuation; refill; drawdown	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Mac Donagh et al. 2009	examine how hydrology (rainy years with a lot of surface spill and higher renewal rates) affect phytoplankton and zooplankton	1	water level fluctuation; selective withdrawal	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy

Table 4 (continued). A description of each of the studies included in this review, the number of waterbodies in each study, reported management strategies or concerns, and reported response variables.

Study	Aim of study	Number of waterbodies	Management strategy or concern	Reported response variable(s)
Magalhaes et al. 2019	survey the abundance and compositional changes of cyanobacteria in a tropical reservoir and analyze effects of environmental factors using generalized linear models on a 6 year dataset	1	water level fluctuation	phytoplankton microscopy; cyanobacterial toxins
Mendes et al. 2022	evaluate the effects of water volume decreases on cyanobacterial abundance and heterocyst production in semiarid tropical reservoirs during drought	3	drought; drawdown	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Mineeva 2021	examine long term trends in phytoplankton and describe seasonal dynamics	1	water level fluctuation	Fluoroprobe (phytoplankton groups)
Nunes Carvalho et al. 2022	explore effects of hydrological and climate variables on chlorophyll-a in large drinking water supply reservoirs in a semi-arid region	3	drought; water level fluctuation	filtered chlorophyll ($\mu\text{g/L}$)
Olds et al. 2011	compare water quality between a 4 year drought and 3 years of normal conditions	1	drought	sensor chlorophyll ($\mu\text{g/L}$)
Pan et al. 2018	examine how a managed filling of the reservoir affects the phytoplankton assemblage (sampling before, during and after).	1	refill	phytoplankton microscopy
Partyka et al. 2018	improve understanding of <i>E. coli</i> variability along horizontal and vertical profiles in California reservoirs	6	N/A	<i>E. coli</i>
Pham et al. 2021	investigate dynamics of toxic cyanobacteria and microcystin concentration in a tropical reservoir	1	water level fluctuation; drawdown	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy; DNA qPCR
Pham et al. 2022	examine the response of phytoplankton functional groups to a waterbody's hydrologic regime and physiochemical variables	1	water level fluctuation	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Robert et al. 2021	combine microbiological monitoring, hydrometeorological parameters and epidemiological analysis	1	drought	<i>E. coli</i>
Sakharova & Korneva 2018	explore how temperature and water level regimes affect phytoplankton communities in littoral and pelagic regions of a reservoir	1	drawdown	phytoplankton microscopy
Song et al. 2023	examine the effects of selective withdrawal on hydrodynamic characteristics, algal growth limiting factors, and algal blooms	1	selective withdrawal	filtered chlorophyll ($\mu\text{g/L}$)

Table 4 (continued). A description of each of the studies included in this review, the number of waterbodies in each study, reported management strategies or concerns, and reported response variables.

Study	Aim of study	Number of waterbodies	Management strategy or concern	Reported response variable(s)
Su et al. 2017	explore the use of water level regulation to reduce underwater light, thereby preventing blooms of MIB-producing cyanobacteria	1	drawdown	single cyanobacterial taxon
Xiang et al. 2021	explore effects of staged impoundment on water quality in the Three Gorges Reservoir	1	water level fluctuation	<i>E. coli</i>
Xiao et al. 2016	investigate the succession of phytoplankton over 2 years in the backwater of a tributary to the Three Gorges Reservoir	1	water level fluctuation; refill; drawdown	filtered chlorophyll ($\mu\text{g/L}$); phytoplankton microscopy
Yan et al. 2023	explore the interactive effects of hydrological characteristics and in-lake physicochemical parameters on phytoplankton community structure	1	water level fluctuation	phytoplankton microscopy
Ye et al. 2022	examine whether water level fluctuation is a causal factor driving the dynamics of phytoplankton biomass and whether water level regulation can be used to control blooms	1	water level fluctuation	filtered chlorophyll ($\mu\text{g/L}$)
Zhao et al. 2016	evaluate water quality of Three Gorges Reservoir from 2010–2013	1	water level fluctuation	<i>E. coli</i>
Zhou et al. 2022	assess whether adjustments in water level can prevent harmful phytoplankton blooms in the Three Gorges Reservoir using long-term phytoplankton phenology data	1	drawdown; water level fluctuation	sensor chlorophyll ($\mu\text{g/L}$); remotely sensed chlorophyll

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