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Impacts of climate-induced drought on lake and reservoir biodiversity and ecosystem services: A review

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Abstract Intensifying extreme droughts are altering lentic ecosystems and disrupting services provisioning. Unfortunately, drought research often lacks a holistic and intersectoral consideration of drought impacts, which can limit relevance of the insights for adaptive management. This literature review evaluated the current state of lake and reservoir extreme drought research in relation to biodiversity and three ecosystem services. The study findings demonstrated that few articles linked or discussed drought implications with one or more ecosystem services, instead focusing primarily on biodiversity. Drought effects on biodiversity varied among species and taxonomic groups. In the limited literature that included ecosystem service provisioning, droughts had a general negative effect. Drinking water supply can decrease and become more costly. Decreasing water flow and volume can reduce hydropower generation. Degraded water quality can also impact recreation. Future intersectoral collaborations and research on intensifying droughts should support adaptive management efforts in mitigating drought impacts.

Keywords Adaptive management · Climate change · Drinking water · Extreme events · Hydropower · Recreation

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INTRODUCTION

Lakes and reservoirs are socio-ecological systems within the landscape that provide significant value to both natural and human-built communities (e.g., Reynaud and Lanzanova 2017). With the latter, these systems offer value through the production of ecosystem services (here defined as benefits that people receive from functioning ecosystems; Comberti et al. 2015). Through the free provisioning of these services, human communities receive numerous products, experiences and supporting processes (Reynaud and Lanzanova 2017). The Common International Classification of Ecosystem Services categorizes the types of services as provisioning (e.g., material and energy needs), cultural (e.g., non-material characteristics that affect well-being), or regulating and maintenance (e.g., processes that maintain an environment suitable for humans; Czúcz et al. 2018).

Service availability can be limited or stalled if the underlying ecosystem functions are altered. This can occur through disruption of lake dynamics. For instance, disturbances can lead to reduced biological diversity, reduced resilience against pressures (Grantham et al. 2019) and shifted functioning of the ecosystem. Given the importance of these services to human communities, protecting and preserving lake health and functions are of high interest to management. Lentic systems, however, are subject to the range of pressures located within their catchment (Adrian et al. 2009; Falkenmark et al. 2019). While many sources of degradation are well researched, further insights into the repercussions of some long-term stressors (e.g., climate-intensified droughts) are needed in addition to research on how climate and anthropogenic stressors may interact. It is anticipated that shifting precipitation variability toward fewer and more intense annual events will increase the likelihood of experiencing pronounced, widespread periods of dryness (Bond et al. 2008; IPCC 2021). These types of drought events, which can be defined as atypical climatic events that affect ecosystem structure or functions past typical ranges (Smith 2011), can have strong negative effects on lentic ecosystems (Aldous et al. 2011; Mosley 2015; Lennox et al. 2019; Şen 2021). Scientific consensus indicates that these droughts can impair ecosystem functions, disrupt services and have societal implications (Munang et al. 2013; Lynch et al. 2022; Vári et al. 2022). The magnitude of these effects on lentic systems can further be influenced by ecosystem characteristics such as geographical location (Mosley 2015). While all regions are expected to experience climate change and the associated extreme events (e.g., Hari et al. 2020), certain regions are projected to have large increases in severe drought pressures. These include areas in already vulnerable or water-stressed areas such as southern Europe, West Africa (IPCC 2021) and Australia (Bond et al. 2008).

Both climate change and anthropogenic actions are causing ecosystems to lose resilience (Vasseur and Andrade 2024). Lakes and similar lentic water bodies are particularly vulnerable to the interaction effect of stressors and human interventions which can exacerbate degradation (Soranno et al. 2014; Magee et al. 2019). Given that many systems worldwide are already in a degraded state, the risk of further alteration can have widespread consequences (Jenny et al. 2020). With consideration of the range of stressors that are affecting lentic systems and their projected intensification, it is necessary that concerted efforts be made to bolster the resilience of systems against further breakdown of health and functions (Munang et al. 2013). Risk assessment of these ecosystems needs to include an understanding of all the ways that the water bodies will be affected by disturbance and how shifts in the system's social and ecological processes may influence each other (e.g., Dittmann et al. 2024). Similar comprehensive understandings of the numerous stressors impacting lakes will be necessary for curating management plans that resolve the underlying challenges. As there are many uncertainties due to these stressors occurring simultaneously, becoming more intense and happening more frequently, it can be difficult to fully identify the range of effects.

Adaptive management, a method that utilizes iterative cycles to allow "simultaneously managing and learning about natural resources" (Williams 2011), can provide a flexible and reflective approach for adjusting the interventions and measures that are applied to ecosystems. Planned interventions can therefore be adjusted as new research insights address uncertainties, different stressors exert influence on the system, or as the target management goal shifts (Hillman et al. 2005). This management method has been discussed in theory (e.g., Hillman et al. 2005; Pahl-Wostl 2007; Stoffels et al. 2024) and applied in practice (e.g., Huntjens et al. 2011; Zeff 2011; Mandarano and Mason 2013) for many stressors. Currently with lentic ecosystems, there is a growing tendency in their climate adaptation toward heavy rains and floods, while much less attention has been devoted to building resilience against drought events. An adaptive management approach with its intentional factoring in of steps for reflection, learning and adaptation (Fabricius and Cundill 2014) can facilitate integration of insights that address existing uncertainties about climate-extreme or intensified droughts effects. This could include, for example, implications from the event's prolonged occurrence, delayed effects or synergy with other pressures (e.g., Szejgis et al. 2024). This method can also incorporate the economic, regulatory and other affected aspects of ecosystem services into decision-making to consider broad, intersectoral effects and measures (e.g., Pahl-Wostl 2007).

Scientific research can trace the cause–effect impacts from extreme drought events to the provisioning of ecosystem services (e.g., Birgé et al. 2016), and these findings can assist management decision-making with implementing measures based on the best available knowledge of ecological concerns and social repercussions (e.g., Mens et al. 2022). In this study, we reviewed the published literature on extreme and intense drought effects in lake and reservoir systems to assess whether the studies incorporated intersectoral considerations by including the effects on ecosystem service provisioning. Specifically, while much drought research has focused on the effects of these events on the biotic community and abiotic variables of ecological systems, we were interested in synthesizing whether links have been made with event occurrence and its impacts on lentic ecosystem services (e.g., Kadykalo et al. 2021). We asked, "How does drought affect biodiversity and ecosystem service provisioning (drinking water, hydropower and recreation) in lentic water bodies?" Biodiversity was selected as a comparison to ecosystem services for this review because species diversity influences ecosystem dynamics and functions, which in turn can affect services provisioning (Tilman et al. 2014; Heino et al. 2021). Drinking water and hydropower were selected as provisioning services and recreation as a cultural service to represent services that are socially relevant and visible but expected to be underrepresented in the literature. This review included a wide range of publications to elucidate the extent that intersectoral impacts are currently considered in drought research. Through bringing together diverse research findings, this study provides a broad view of the pathways in which extreme droughts affect biodiversity and the ecosystem services. From our findings, recommendations were made on how to advance our understanding of drought intersectoral implications and support adaptive management strategies ahead of worsening climate change.

METHODOLOGY

Our systematic literature review consisted of three steps: literature search, abstract and keywords screening, and full article screening (Fig. 1).

Literature search

We used the Web of Science (WoS) database for the literature review as it is renowned (Li et al. 2018), commonly used in environmental research due to its broad coverage in natural and social sciences (e.g., Stockwell et al. 2020; Lv et al. 2021; Shi et al. 2022), and has notable overlap with other reputable scientific publication databases (Mongeon and Paul-Hus 2016). The keyword string "drought* AND (lake* OR reservoir*) AND ((extreme* OR intens*) AND (drink* OR energy OR hydroelectric* OR hydropower OR recreation* OR fish* OR swim* OR boat* OR richness OR abundance OR diversity))" was used to search for English language papers in the WoS published from 1990 until February 2020. These keywords were selected to screen for papers that incorporated elements of our research question, including the occurrence of intensified or extreme droughts in lake and reservoir systems and the inclusion of biodiversity or an ecosystem service of interest in the narrative. Three-hundred papers were identified and considered for the review.

Abstract and keywords screening

The abstracts and keywords of the 300 papers were screened based on three criteria: (1) did the abstract and/or keywords mention a lake or reservoir; (2) was extreme or intensified drought mentioned in the abstract and/or keywords; and (3) was biodiversity and/or at least one of the three ecosystem services (water quality, hydropower and recreation) mentioned in the abstract and/or keywords? Papers had to meet all three criteria to be included. Each abstract was assessed by two reviewers. When the two reviewers had different opinions about the suitability of a paper for the study, a third reviewer was assigned to assess the relevance of the abstract and keywords. Following these steps, 118 papers met our criteria.

Full article screening

The 118 papers were reviewed and filtered for those relevant to the study criteria. Papers were removed if they did not meet the criteria of studying: (1) lakes and/or reservoirs, (2) extreme or intensified droughts and (3) biodiversity and/or one of the ecosystem services. A total of 78 papers remained after this final screening. Content analysis

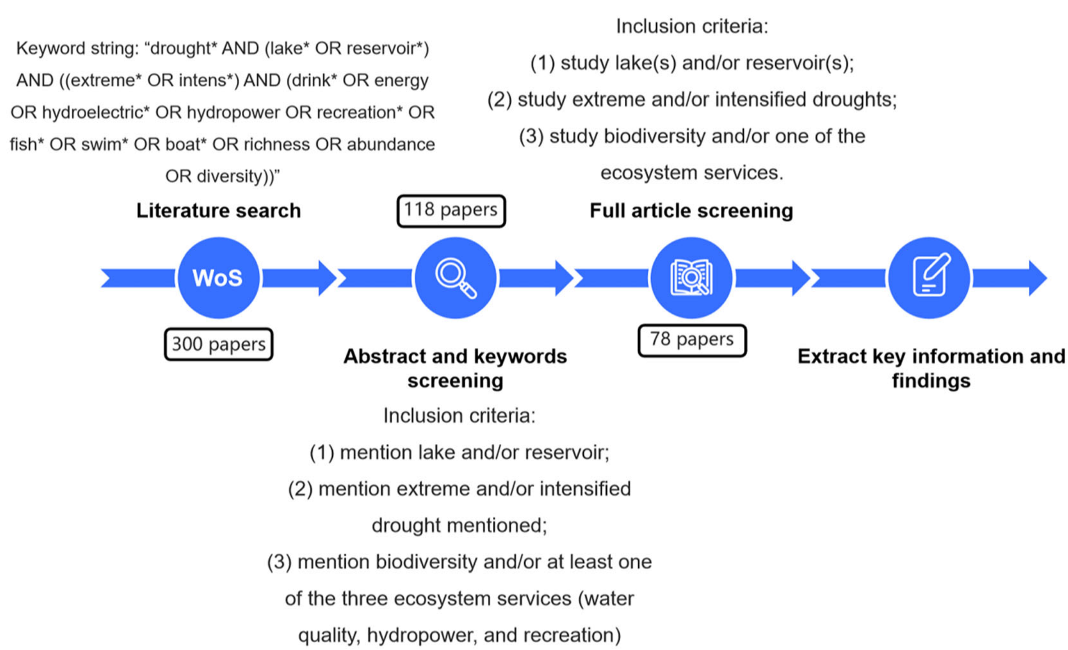

Fig. 1 Flowchart showing the steps executed for searching and screening literature. During abstract and keywords screening and full article screening, only papers that met all three criteria were included in the review

of the publications was done (Bengtsson 2016; Paré and Kitsiou 2017), and the key findings about drought effects on biodiversity and/or each ecosystem service were extracted. Insights into the primary and secondary focus of each paper (i.e., biodiversity, drinking water, hydropower or recreation) and the study site locations were also recorded. The template from the full article screening with example data and information collected from the papers is provided in Table S1.

RESULTS

Profile of literature dataset

Among the 78 papers that passed our full article screening, most papers studied drought impacts on biodiversity (56 papers), followed by impacts on drinking water and hydropower (13 papers for each topic). Only two papers discussed implications on recreation (Table S2). Most of the water bodies in our literature review were located in North America (69), followed by South America (37), Africa (12), Europe (9), Asia (9) and Oceania (5; Fig. 2). Many regions that are vulnerable to drought, such as Central and West Africa, were significantly understudied (Figure S1).

Linkage between biodiversity and ecosystem services in drought studies

Eighty-seven percent of the publications (68 papers) did not have a secondary focus, indicating most of them focused on only one aspect (i.e., biodiversity or one of the ecosystem services) of drought impacts (Fig. 3). Among the few papers that studied or discussed a secondary focus, we found links between biodiversity and drinking water, between biodiversity and hydropower as well as between hydropower and drinking water. Out of these papers that addressed more than one topic, drought impacts on biodiversity were often linked with implications on drinking water quality. In comparison, papers primarily focused on drinking water occasionally mentioned biodiversity (e.g., microbiome and cyanobacteria).

Effects of droughts on biodiversity and ecosystem services

Biodiversity

The literature included in our review showed that extreme droughts could generally influence biodiversity directly by decreasing water level and indirectly through nutrient enrichment and alteration of food quantity and quality. We found that there were variations in the way that droughts affected organisms within and between taxonomic groups

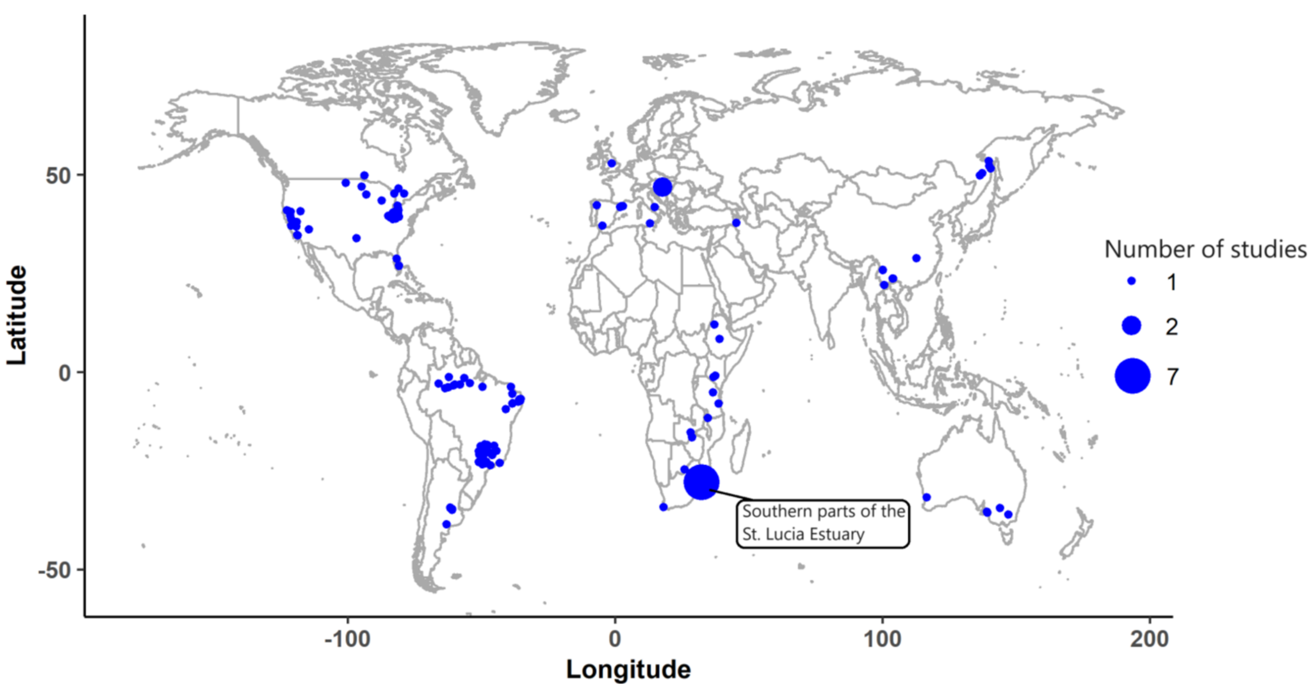

Fig. 2 Geographical distribution of the locations of the ecosystems in the scientific publications that were included in the systematic literature review. Dot size is scaled to indicate the number of studies that were located in different areas

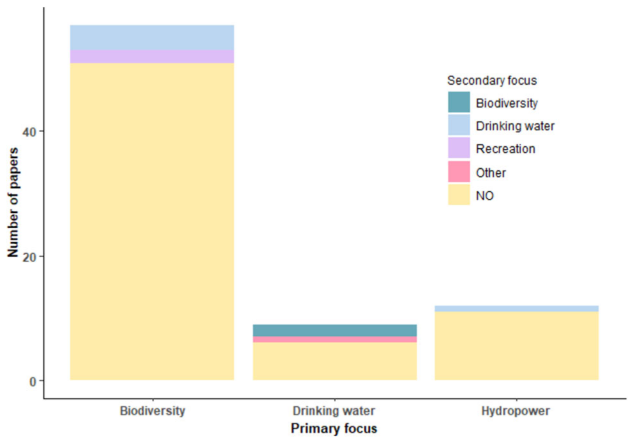

Fig. 3 Bar graph of scientific publications with primary focuses of biodiversity, drinking water and hydropower. Bars are color-coded to illustrate whether the publications only included the primary focus (yellow) or whether a secondary focus was also incorporated or discussed (green, blue, purple, red)

(Table S3). Here we summarize the general trends of organismal responses based on the findings presented in the studies. It was beyond the scope of our study to delve into the specific underlying mechanisms that induced the responses and variations.

Microbial community Microbial communities were only studied in three papers in our review but showed different drought responses in different systems. The composition of a sediment microbial community in a large water-storage reservoir in Australia significantly changed during extreme droughts (Boulding et al. 2008). In a large subtropical lake in Florida, USA, drought caused no changes in bacterial biomass (Havens et al. 2007). For a lake that relies on waterbird guano inputs as a nutrient source, the nitrogen and phosphorus inputs from flamingos (*Phoenicopterus roseus*) declined during droughts. This resulted in an observed reduction in nutrient availability for prokaryotes and viruses (Batanero et al. 2017).

Phytoplankton Most studies suggested a positive association of extreme drought with total phytoplankton abundance and biomass, likely due to nutrient enrichment (e.g., Muir and Perissinotto 2011; Bogatov and Fedorovskiy 2016). However, there were situations in which declines or no changes in phytoplankton biomass were observed (Havens et al. 2007; Crossetti et al. 2019). Phytoplankton community composition often shifted with droughts. For example, diatom biovolume decreased by 50% while non-diatom phytoplankton biovolume increased by 400%. Nitrogen-fixing cyanobacteria growth in particular was promoted during droughts (Howard and Noble 2018).

Zooplankton Cladocerans often showed declines in abundance and biomass during extreme droughts. Increased fish predation pressure due to reduced water volume as well as cyanobacteria blooms during droughts could cause the reduction in cladoceran density (e.g., Ji et al. 2017). In comparison, copepod and rotifer responses to droughts were varied and can depend on the species present in the community and the specific environmental conditions.

Macroinvertebrates (benthic macroinvertebrates, aquatic insects and mussels) Extreme droughts adversely affected benthic macroinvertebrate assemblages and altered community composition. General insect abundances have also been observed to decrease during droughts (Deacon et al. 2019). However, drought impacts on insects can vary according to current and historical water quality conditions and assemblage composition (e.g., opposite directions of change in Diptera abundance in Sommer and Horwitz 2001 and Jovem-Azevêdo et al. 2019). Mussels, particularly large individuals, appeared to be intolerant to droughts (e.g., Churchill et al. 2017).

Fish Extreme drought adversely affected fish by reducing their total abundance, biomass and biodiversity. Changes in fish assemblage composition were also found in several case studies, indicating that drought impacts were non-uniform among species. For instance, drought increased the abundance of planktivorous, herbivorous and detritivorous fishes. In contrast, reductions were observed in the abundance of carnivores and omnivores (Freitas et al. 2013; Röpke et al. 2017; Tribuzy-Neto et al. 2017). Furthermore, the biomass of native species was substantially lower in the Sítios Novos reservoir (Brazil) during droughts, resulting in the dominance of non-native species (Bezerra et al. 2018).

Other vertebrates We found few publications that addressed aquatic or semiaquatic vertebrates other than fish. In these studies, extreme droughts negatively influenced the occupancy of the native spotted frog (*Rana luteiventris*; Arkle and Pilliod 2015) and waterbirds (Chrystal and Scharler 2014; Batanero et al. 2017).

Plants The effect of extreme drought on aquatic and semiaquatic plants tended to be species-dependent. Lakebed assemblages and aquatic plants were often vulnerable to droughts while submerged lakeshore vegetation, such as cattail (*Typha* spp.; Winter et al. 2005), was resilient to or even favored by droughts.

Drinking water

Extreme droughts have been found to impact the water quantity of lakes and reservoirs along with their physical and chemical qualities (Table S4). These effects can result in chemical or microbial contamination as well as toxic cyanobacterial blooms, thereby causing the water to be unsuitable for human consumption.

Reduction of water supply capacity Extreme droughts can restrict water supply coverage and increase the cost of supply. For example, a reduction in water supply capacity can lead to water usage restrictions (e.g., Siderius et al. 2018) and extra costs for pumping water from other sources (e.g., Soares et al. 2019).

Altered water physical properties Changes in lake and reservoir hydrodynamics due to droughts can have profound consequences on water physical properties and subsequently on general drinking water supply. For instance, extreme drought can increase water temperature and change the water mixing regime (e.g., from monomictic to polymictic), resulting in increased turbidity from nutrient and sediment resuspension (Barroso et al. 2018; Soares et al. 2019).

Increased nutrient and chemical contaminant levels Increased concentrations of nutrients and chemical contaminants have been reported during and after extreme droughts. During droughts, catchment runoff to lakes and reservoirs may decrease relative to the discharge from point source pollution (e.g., wastewater and mine drainage). This can lead to a net increase in the concentration of nutrients as well as contaminants such as odor compound 2-methylisoborneol, pharmaceuticals and endocrine disrupting compounds in water bodies (Winston et al. 2014; Wright et al. 2014; Khan et al. 2015). Precipitation following extreme droughts can also mobilize and flush sediment and nutrients that have accumulated in the catchment into receiving lakes and reservoirs, causing a rise in their concentrations (Wright et al. 2014; Khan et al. 2015). Additionally, dissolved organic carbon produced during droughts tend to be more hydrophilic and are difficult to remove by conventional treatment methods, therefore requiring additional investments in water treatment processes (Khan et al. 2015).

Microbial contamination and cyanobacterial blooms Extreme droughts can lead to microbial contamination in surface water systems. For example, microbial contamination (*Giardia* and *Cryptosporidium*) occurred in a lake that supplies drinking water to a nearby town in southeastern Australia after a prolonged drought (Wright et al. 2014). This was due to the accumulation of fecal matter in connected catchments during the drought which was then flushed into the lake following the first rains post-drought (Wright et al. 2014). Droughts can also promote nutrient enrichment and the subsequent proliferation of algal or cyanobacterial blooms, some of which release toxins that can cause liver damage, skin diseases, neurological impairments and mortality (e.g., microcystins and cylindrospermopsins; Paerl and Paul 2012; Wright et al. 2014; Walter et al. 2018).

Hydropower

Extreme droughts can reduce hydropower generation and revenue by decreasing water inflow and volume in reservoirs (Freitas and Soito 2009; Oludhe et al. 2013; Kern et al. 2015; Vale et al. 2016; Forrest et al. 2018; Gjorgiev and Sansavini 2018; Liu et al. 2018; Siderius et al. 2018). For instance, in Zambia, the electricity supply was reduced by 40–50% of the baseload due to insufficient hydroelectricity generation during the drought period in 2015 (Siderius et al. 2018).

As a result of decreased hydroelectricity generation, the reliance on other energy resources can increase and result in both higher costs and elevated greenhouse gas (GHG) emissions (Kern et al. 2015; Zambon et al. 2015, 2016; Tarroja et al. 2016; Forrest et al. 2018). Thermal energy (e.g., burning of natural gas) is often the alternative energy generation approach during droughts to address the shortage in hydroelectricity production. However, this energy source has higher financial costs and GHG emissions (Kern et al. 2015). In Brazil, the cost per MWh of electricity increased by about 60% under extreme drought conditions during 2012–2015 because thermal energy was required to compensate for the hydropower generation shortage (Zambon et al. 2015, 2016).

Recreation

Despite the economic and cultural value of lake and reservoir recreational uses (Börger et al. 2021), this review had only two papers that mentioned the impacts of extreme droughts on recreation. Both papers qualitatively discussed how drought-induced toxic cyanobacteria blooms adversely affect recreational uses by diminishing water quality. For example, a decrease in water quality can lead to consequences such as degradation of recreational fisheries (Paerl and Paul 2012) and reduction in the esthetic appeal of lakes to park visitors and campers (Howard and Noble 2018).

DISCUSSION

Research is needed on extreme climatic events such as droughts as they are a relatively recent pressure being exerted upon lentic systems, they are projected to become more intense and there are many uncertainties about how water systems will be impacted. The scientific insights gained from drought studies can support management decisions in enhancing the resilience of freshwater ecosystems. In this study, we reviewed current scientific literature on climatic-intensified and extreme droughts in lake and reservoir ecosystems to assess whether they included intersectoral implications of the disturbance. Specifically, through reviewing drought literature for considerations of biodiversity (as a representative of ecosystem processes that influence functions) and select ecosystem services (drinking water, hydropower and recreation), we began tracing cause–effect relationships across intersectoral lines. We found that the majority of scientific publications looking at drought impacts on lentic water systems considered the impacts of biodiversity (56 publications) as compared to ecosystem services (13 drinking water, 13 hydropower and 2 recreation publications), with few linkages between them. "Biodiversity," "Drinking water," "Hydropower" and "Recreation" sections discuss the literature review findings by biodiversity and ecosystem service. "Science research for adaptive management of lentic freshwater systems" section focuses on adaptive management practices and the role of drought research.

Biodiversity

Biodiversity is a vital aspect of aquatic systems that builds the foundation for complex ecosystem functions and uses (Comberti et al. 2015). Ecosystems that have great biodiversity are often considered resilient and adaptable to changes (Poff et al. 2012). In the context of ecosystem services, greater biodiversity permits a strong basis for providing and continuing the provisioning of services. In this review, only a few papers about cyanobacteria linked droughts' influence on biodiversity with ecosystem services, thereby introducing limitations in our ability to estimate the contribution of the biome toward ecosystem service provisioning (e.g., drinking water quality and recreational activities). We recommend that more studies in the future look at the link between biodiversity and ecosystem services to better predict and manage the socioeconomic impacts of droughts.

Although abundant research has examined drought impacts on biodiversity at scales ranging from individuals to communities, studies were not evenly spread across taxonomic groups and food web interactions were rarely examined. This literature review found that the microbiome, macroinvertebrates and vertebrates (aside from fish) in lakes were not well studied. Additionally, of the groups that were represented, there were strong variations in drought responses among different species and taxonomic groups. Previous studies suggested that the among- and within-species variations in responses to climate change could be driven by biotic factors, such as phenotypic plasticity and genetic diversity (Doi et al. 2017; Amano et al. 2020), as well as multi-scale abiotic factors, such as lake morphometry, watershed land use and regional climate features (Soranno et al. 2014). As a result, conclusions from existing research on some species may therefore have limited applicability to understudied species. These findings demonstrate a need to study diverse species to acquire a broader, comprehensive understanding of the impacts, which can support species- and functioning-specific management and conservation. Additionally, while food web interactions can be altered by droughts, the papers we reviewed have predominantly focused on single taxa, and impacts on interactions among different organisms were not well explored. Since food web interactions can indirectly affect organisms that are drought-tolerant and influence organismal and ecosystems' responses to disturbances (e.g., greater ecosystem vulnerability to drought due to increased predation pressure; Bezerra et al. 2018), this gap may increase uncertainties when generalizing and applying research findings to management (Zeff 2011).

Drinking water

Lentic systems are frequently used as a source of drinking water for human communities ranging from metropolitan to rural. Current research supports that climate-intensified droughts will exacerbate scarcity by diminishing supply and contributing to both the technical difficulties and the cost of water treatment. With potable water supply becoming more and more scarce from increasing demand and decreasing availability (Sivakumar 2011; United Nations 2023), unchecked declines in lake and reservoir health can place further pressure on communities that are currently or close to becoming water-stressed. Understanding how various drivers can impact drinking water quality and quantity will therefore be important socially and economically (Khan et al. 2015).

Findings from research on extreme droughts can be applied to forecasting drought impacts, planning management strategies, and enhancing the resilience of and adapting lentic ecosystems for impending extreme climate events and stressors (e.g., Garnier and Holman 2019). Furthermore, the monitoring of disturbance impact and the management of drinking water sources can be further strengthened by expanding the biodiversity indicators from cyanobacteria, which is the dominant indicator in current research, to other taxonomic groups that are sensitive to environmental changes and provide prompt responses (González and Roldán 2019). For example, benthic macroinvertebrates such as Oligochaetes and Mollusca can be effective bioindicators of drought-induced drinking water quality changes as they react rapidly to water level, temperature and water chemistry changes (Azevêdo et al. 2022).

Hydropower

Hydropower is one of the most efficient renewable energies that can help reduce greenhouse gas emissions in the coming decades (Gleick 2016; Zhong et al. 2021). However, hydropower generation is sensitive to changes in hydrological conditions and at risk of drought impacts (Wasti et al. 2022). Presently, up to 75% of existing hydropower capacity in Europe, North America, the Middle East and North Africa is located in areas where drought duration is projected to be more extreme and prolonged due to climate change (Paltán et al. 2021).

Studies in our literature review discussed the negative effects of droughts on reservoir hydropower generation capacity and the costs of alternative energy generation approaches. It is important to note that the influence of hydropower plants on downstream lake ecosystems during extreme droughts was rarely examined (Gao et al. 2024). While biodiversity and hydropower generation may not influence each other directly, there can be conflicts between power production and downstream conservation efforts during extreme droughts due to changes in the hydrological regime and the need to fulfill increased energy demands (water–energy–ecosystems nexus; Zhong et al. 2021). An understanding of the interactions between these systems and the potential consequences can help alleviate this predicament, which in turn can support the design of adaptive management initiatives to balance socioeconomic demands with downstream aquatic ecosystem conservation (Dyson et al. 2008; Finger et al. 2007; Zhong et al. 2021).

Recreation

The direct and indirect recreational uses of lakes and reservoirs can have substantial economic benefits (Boyer et al. 2017; McDougall et al. 2020; Börger et al. 2021; Darby et al. 2021). However, climate change disturbances can jeopardize these uses by exacerbating water level fluctuations, inducing competing demands for water and degrading water quality (Boyer et al. 2017; Darby et al. 2021). Few studies in our literature review focused on the impact of extreme droughts on lake and reservoir recreational uses. Potential reasons for this could be that the relevant data were not always publicly available or the impacts were outlined in municipal and government reports (e.g., Crowley et al. 2020) which were not included in our review. Additionally, investigating the impacts of extreme or climate-intensified droughts on recreation requires insight and research collaboration across multiple disciplines (e.g., ecology, economy and management), thereby adding complexity to the research of this topic.

While recreation-related papers in our review focused on the impacts of cyanobacterial blooms, other aspects of recreation in lakes and reservoirs can also be affected by drought-caused changes in the physical and biological aspects of water bodies. The recreational value of some lentic system uses can fluctuate depending on water levels and ecosystem conditions (Boyer et al. 2017). For example, recreational fishing can be impacted by changes in fish habitat (Darby et al. 2021). Lower lake levels, increased surface water temperatures and altered stratification patterns can lead to generally poorer quality habitats for the fish, thereby decreasing fish density and reducing angling value (Darby et al. 2021; Jeanson et al. 2021). Additionally, smaller lake surface area and reduced surface inflow caused by extreme droughts can reduce local boat traffic, affecting tourism and the economy (Wlostowski et al. 2022). Furthermore, decreased water levels can concentrate pathogens, which promote the spread of waterborne diseases that can impact activities such as swimming and boating (Patz et al. 2008). Future research can integrate a wide range of extreme and intensified drought impacts on ecosystem processes with the practical implications for recreational activities to foster an intersectoral understanding of the outcomes of these extreme events.

Science research for adaptive management of lentic freshwater systems

Our study highlights the urgent need for research that links ecosystem drought response with ecosystem service provisioning. This link will be important for developing and adjusting adaptive management plans which have iterative cycles that permit opportunities to respond as dynamic ecosystems and stressors change over time. Science can support this process as research can extensively trace the cause–effect relationships that drought occurrences have on lentic freshwater systems (e.g., Rounsevell et al. 2010). Specifically, abundant research has delved into projections of future climatic events (e.g., Iturbide et al. 2020; Adamo et al. 2021; Lee et al. 2023). Science has also extensively investigated the links between climatic events and the effects to ecosystem functions through methods including model simulations, controlled system experiments and observations of event occurrence (e.g., Perales et al. 2020; Graham and Vinebrooke 2009; Li et al. 2017). Disturbance of the underlying functions of ecosystems can similarly be traced to its effect on service provisioning (e.g., Banerjee et al. 2013). Through highlighting the need for more research in this area in order to support management goals,

Table 1 Summary of key findings and future research directions from the present review on biodiversity and ecosystem service implications for lakes and reservoirs in extreme drought studies. Example management actions are provided for biodiversity and for each ecosystem service

	Findings from current literature	Potential direction for future research	Example management actions
Biodiversity	• Extreme droughts affect biodiversity, but the impacts vary greatly among species and taxonomic groups	• Emphasize implications of biodiversity on ecosystem services provisioning under extreme drought conditions • Conduct more research on understudied species and taxonomic groups' responses to extreme drought • Conduct more research on the impacts of drought on food web interactions	• Identify and develop plans for vulnerable or important species (Reside et al. 2014) • Create or maintain habitats (e.g., protected areas; Ford et al. 2011; Reside et al. 2014; Gillingham et al. 2024)
Drinking water	• Extreme droughts reduce drinking water supply and quality • Extreme droughts increase difficulties and the cost of water treatment by degrading water quality	• Expand the bioindicators from microbiome and cyanobacteria to other ecologically and/or socioeconomically important, sensitive species to strengthen drought management	• Incorporate extreme drought projections into planning (Wright et al. 2014) • Diversify drinking water sources (Khan et al. 2015) • Establish routine water quality and bioindicator monitoring (Wright et al. 2014) • Adjust methods to treat altered quality of water (e.g., Khan et al. 2015) • Continue improvement of technology and increase knowledge (Wright et al. 2014)
Hydropower	• Extreme droughts decrease hydropower generation capacity • Extreme droughts result in the shift of energy generation approach, increasing energy generation costs and GHG emissions	• Study the influence of hydropower plants on downstream lake ecosystems during extreme droughts	• Develop a forecasting or early warning system (Georgakakos et al. 2012) • Increase water storage before upcoming drought (Tayebiyan et al. 2019) • Develop and diversify sustainable renewable energy sources (Cerović & Maradin 2014) • Incorporate downstream systems in operational policies (Tayebiyan et al. 2019)
Recreation	• Extreme drought-induced cyanobacterial blooms can negatively affect recreational use of lakes and reservoirs	• Conduct more intersectoral research on the impacts of extreme drought-induced water level decline and ecosystem changes on recreation	• Establish routine lake and reservoir water quality monitoring (Jedd et al. 2019) • Develop a forecasting system (Jedd et al. 2019) • Enact catchment measures to reduce the amount of accumulated pollutants (Tingley III et al. 2019) • Create accessible habitat for vulnerable species during drought conditions (Tingley III et al. 2019) • Establish communication pathway to provide public with relevant information (Jedd et al. 2019)

future studies can expand their scope to include ecosystem services. With insights into all these connections, management organizations can create informed plans for improving or maintaining the resilience of ecosystems (Loucks 2021).

In addition to studies on specific water systems or interaction pathways, communication of research insights can be done through synthesizing existing knowledge. Scientists can periodically inventory the current state of drought knowledge and make links with ecosystem services provisioning to produce summaries that assist decision-makers. Facilitating the dissemination of scientific insights through a literature review approach could provide managers with relevant information that is new or inaccessible (e.g., paywalls). This study presents an example of this practice as this literature review discusses how current science approaches intersectoral consideration of extreme drought impacts and where there are gaps in the insights that might be useful for decision-making processes. Below we summarized the findings from current research on biodiversity, drinking water, hydropower and recreation implications in extreme drought studies (Table 1). We also listed potential directions for future research that can help facilitate intersectoral efforts and identified examples of management actions that could support biodiversity and ecosystem service provisioning.

While this study distilled relevant findings regarding the need for intersectoral considerations of socio-ecological systems in research going forward, these findings could be complemented with further investigation. For example, a review including the abiotic alterations of systems due to extreme drought events can elucidate the mechanisms behind biodiversity effects. Additionally, our review focused on three highly visible ecosystem services. Subsequent studies could look at different provisioning and cultural services (e.g., Chang and Bonnette 2016) or at regulating and maintenance services (e.g., Kadykalo et al. 2021). This could include changes in ecosystem services in both the affected water system and the exposed lakebed (e.g., exposed lakebed as new habitat and source of GHGs; Bunbury et al. 2020; Cobo et al. 2024). Further, our study was also rooted in an ecological perspective of drought cause–effect impacts and whether that knowledge was being connected to societal implications. Other perspectives such as economic or regulatory could be assessed using different keywords to provide a broader understanding of the affected sectors. A review could also be undertaken on publications that already combine two or more perspectives on ecosystem service provisioning under extreme drought conditions.

NEXT STEPS

More information will be needed to plan for the anticipated effects of climate-intensified and extreme drought. In the papers that were available in this literature review, few connected drought occurrences to effects on lentic freshwater ecosystem services. Broadening scientific perspectives to include links to ecosystem services can make strides in capturing a more holistic understanding of drought impacts and assist with informing management interventions. In addition to the recommendations above, scientists can take steps toward establishing collaborations with ecosystem managers to define questions and co-produce knowledge that is relevant for existing management challenges (Grantham et al. 2019). For example, applied research can provide insights for targeted needs that complement general knowledge of the underlying ecosystem processes of intersectoral interactions. Research on the adaptive capacity of lentic systems to the new climate reality can also be useful for management decision-making (e.g., Aldous et al. 2011). Taking strides now to bridge the intersectoral divide and to bolster knowledge about drought effects can support the development of resilience-oriented management plans in preparation or in response to extreme drought occurrence.

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Declarations

Conflict of interest The authors declare there is no conflict of interest.

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