

Impacts of Drought on Water Quantity and Water Quality

Sara Gutierrez Diaz¹, Joseph E. Quansah¹, Souleymane Fall¹, Shamim A. Begum^{2*}

¹Department of Agricultural and Environmental Sciences, Tuskegee University, Tuskegee, AL, USA

²Department of Chemical Engineering, Tuskegee University, Tuskegee, AL, USA

Email: *sbegum@tuskegee.edu, sdiaz6869@tuskegee.edu, jqansah@tuskegee.edu, sfall@tuskegee.edu

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Abstract

The frequency and severity of droughts are increasing globally due to adverse weather conditions and rising human water demands. Drought and the resulting water scarcity not only reduce water quantity but also directly alter water quality, affecting every dimension of freshwater systems. This literature review synthesizes current research on the effects of drought on water availability and quality across diverse hydrologic systems. It examines how drought dynamics, compounded by human activities, reduce water availability and drive physical, chemical, and biological changes-including declines in streamflow and groundwater storage, loss of hydrological connectivity, elevated water temperatures, and nutrient, contaminant, and dissolved oxygen depletion. Evidence indicates that these effects are not confined to specific systems or scales; they interact with existing anthropogenic pressures to degrade water quality and hydrological function, often persisting well beyond the drought period through lagged groundwater recovery and post-drought flushing of accumulated pollutants. Effective responses require moving beyond reactive crisis management toward integrated, long-term adaptive strategies grounded in hydrological understanding and institutional commitment. Significant knowledge gaps remain, particularly regarding post-drought recovery, the cumulative effects of repeated drought events, and the long-term trajectory of freshwater systems under projected climate change.

Keywords

Drought, Water Quality, Water Quantity, Water Management, Adaptive Options

1. Introduction

Drought is one of the most complex and widespread natural hazards, yet it remains one of the least understood. Unlike other hazards such as floods, drought

lacks a universally accepted definition. It is generally categorized into four types: meteorological, agricultural, hydrological, and socio-economic, each representing a different aspect of water scarcity (Bond et al., 2008). Drought is commonly classified into four interrelated types (NIDIS, n.d.). Meteorological drought results from a shortfall in precipitation relative to normal, compounded by the duration of the dry spell. Agricultural drought emerges when soil moisture deficits and limited water availability begin to affect crop performance. Hydrological drought is reflected in reduced streamflow, reservoir storage, and groundwater levels. Socio-economic drought occurs when weather-driven water shortages cause the demand for an economic good to exceed its supply. The four types of droughts are illustrated in **Figure 1**. What makes drought particularly difficult to characterize is that its occurrence is inherently defined by its consequences; it is recognized not by a single measurable event, but by the cumulative impacts it produces over time (Disasa et al., 2026). In this sense, drought stands apart from other natural hazards as a disturbance of deficiency rather than an excess (Bond et al., 2008).

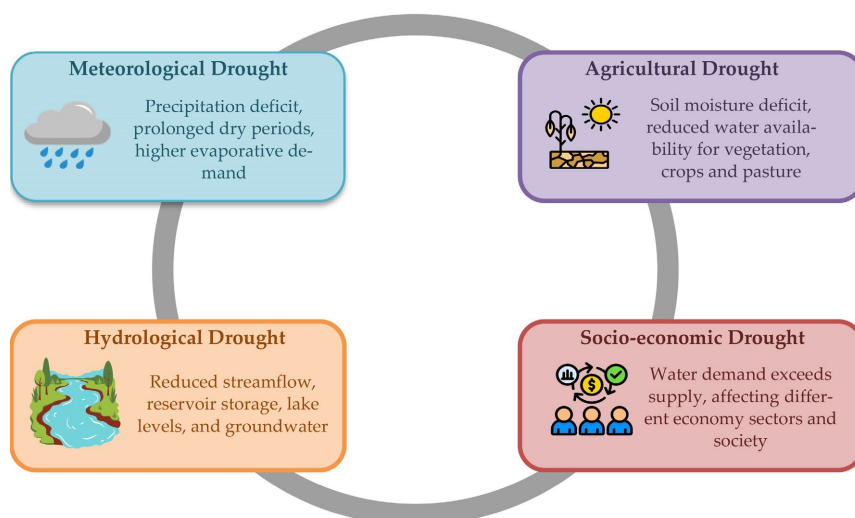


Figure 1. Main types of drought diagram.

This deficiency-based nature also makes drought uniquely difficult to detect. Unlike floods, whose onset is abrupt and identifiable, the beginning of a drought can often only be recognized once it has already been occurring for some time (Humphries & Baldwin, 2003). This ambiguity is compounded by the fact that drought operates as a multidimensional, multiscale phenomenon, characterized by compounding processes and feedback between human and natural systems (AghaKouchak et al., 2021). Whether drought is periodic in nature, driven by adverse weather, or exacerbated by growing water demand remains far from conclusive (Haile et al., 2020).

Despite this uncertainty, there is mounting evidence that drought events are becoming more frequent and severe. Research has demonstrated that droughts are intensifying even in regions experiencing overall increases in total precipitation, raising critical concerns for long-term water security (Park et al., 2026). This trend is

expected to continue, with severe droughts projected to increase across many regions of the world as a direct consequence of climate change (Disasa et al., 2026; Mosley, 2015). The most immediate consequence of this intensification is a reduction in water availability. The failure of rainfall leads to a loss of soil moisture, surface runoff, and groundwater recharge. Thus, the quantity of water accessible across rivers, lakes, reservoirs, and estuaries diminishes (Bond et al., 2008; Van Loon, 2015). However, the consequences of drought go beyond the amount of water available. As water quantity drops, the quality of the remaining water often deteriorates significantly, with long-lasting effects. Reduced flows concentrate pollutants, alter thermal regimes, disrupt nutrient cycling, and restructure the physical, chemical, and biological conditions of aquatic systems (Bond et al., 2008; Mosley, 2015). In many regions, such alterations have created conditions in which water shortages (as the primary consequence of drought) persist even during wet years, making it increasingly difficult to distinguish between water quantity and water quality (AghaKouchak et al., 2021). Freshwater is a limited resource subject to numerous and growing threats (Dodds et al., 2013). Drought-induced reductions in water availability and water quality pose significant risks to hydrological systems and the freshwater supply for human activities. This review synthesizes current literature on the effects of drought on water quantity and quality across natural and engineered hydrologic systems. It examines how adverse weather and human activities are driving intensification of drought, how reduced water availability restructures hydrological systems, and how those hydrological alteration cascade into changes in physical, chemical, and biological properties of water. Finally, it evaluates adaptive responses required to reduce the impacts of drought on water resources.

2. Materials and Methods

This review was conducted as a narrative literature review examining the effects of drought on water quantity and quality across water bodies. The review was guided by the following question: How do drought conditions affect water quantity and water quality across different hydrological systems? A narrative approach was selected to enable a broad, integrative synthesis of findings across diverse hydrological systems.

Literature was sourced from three academic databases: Google Scholar, Scopus, and ScienceDirect. Searches were conducted between March and June 2026. The search strategy included broad terms such as drought, ground water, surface water, water quantity, as well as more targeted searches addressing specific effects of drought on water quality. These included searches related to physical parameters such as turbidity, sedimentation, total suspended solids (TSS), and sediment transport; chemical parameters, including pH, nitrogen, phosphorus, biochemical oxygen demand (BOD), chemical oxygen demand (COD), agrochemicals, and contaminants; and biological and ecological effects of drought. Additional searches addressed drought-related changes in surface water availability, groundwater, hydrological connectivity, and the influence of land use. Similar search concepts and combinations of keywords were applied across the three databases to identify rel-

evant literature. The search was limited to publications from 2000 to 2026 to ensure relevance to contemporary climate conditions, modern water quantity and quality research. The review was limited to studies published in English.

An initial screening of titles and abstracts was performed to assess relevance before full texts were reviewed. Selected titles identified across the three databases were collected and managed using Zotero for reference management and organization. Studies were included if they directly addressed the review question and showcased the relationship between drought conditions and at least one of the following aspects of hydrological systems: water availability, hydrological connectivity, or physical, chemical, or biological water quality parameters. Studies focused solely on terrestrial or atmospheric processes, without a direct link to water bodies, were excluded.

The reviewed literature comprises 80 studies in total. Of these, 24 are review articles with no specific geographic focus, and 7 are global or multi-regional studies. The remaining 49 studies address specific geographic locations, with some spanning multiple countries, yielding 78 country-level observations across 31 countries. This breakdown is presented in **Figure 2**.

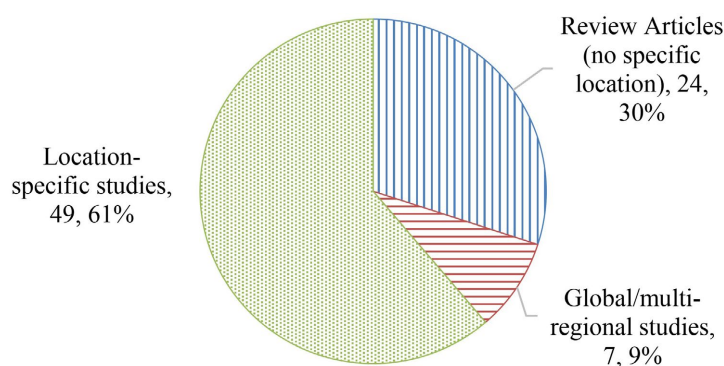


Figure 2. Distribution of studies found by this literature review.

The largest concentrations of site-specific research come from the United States ($n = 14$), China ($n = 8$), and Chile ($n = 4$), with additional representation from Puerto Rico, South America (Brazil, Argentina, Bolivia, Uruguay, Colombia, Ecuador, Paraguay, Peru, Venezuela), Europe (United Kingdom, Germany, France, Netherlands, Austria, Belgium, Luxembourg, Portugal, Switzerland), Asia (South Korea, The Democratic People's Republic of Korea, Iran, Japan, Mongolia, Taiwan Region (China)), Africa (Kenya, Morocco), and Oceania (Australia). This geographic diversity reflects the broad relevance of drought impacts on water quantity and quality across varied climatic, hydrological, and socioeconomic contexts, while also highlighting a notable underrepresentation of research from Africa, Central Asia, and the Middle East—regions particularly vulnerable to drought stress.

Figure 3 presents the temporal distribution of the 80 studies included in this review by publication year and study type. The earliest studies retrieved date to 2003, with publication output remaining low through the late 2000s and early 2010s. A gradual increase is observed from 2015 onward, with the highest number

of studies appearing in 2024 ($n = 10$) and 2025 ($n = 8$), suggesting that research on drought effects on water quantity and quality has received increasing attention in recent years within the retrieved literature. Location-specific studies represent the dominant study type across all years. Review articles appear more consistently from 2015 onward, while global and multi-regional studies are sparse but distributed across the review period. Studies from 2026 ($n = 3$) represent early publications from that year retrieved at the time of the literature search.

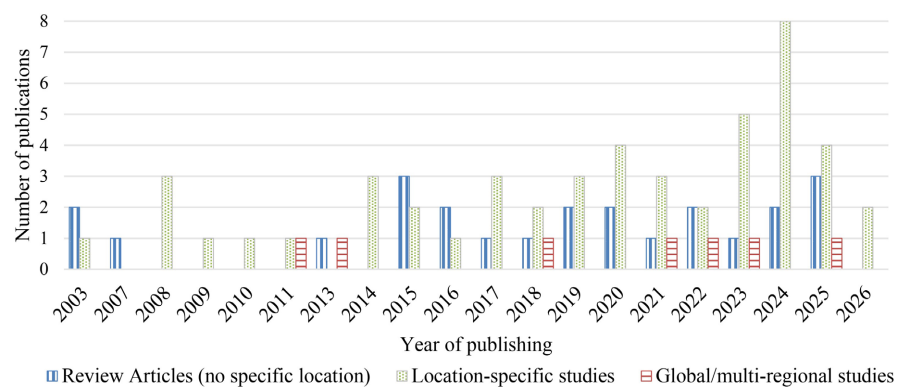


Figure 3. Temporal distribution of studies found by publication year and study type.

3. Adverse Weather and Drought Trends

The relationship between adverse weather and drought is one of the most pressing concerns in contemporary water resources research. While drought has always been a natural feature of climatic variability, there is growing consensus that anthropogenic activities and adverse weather are altering the frequency, severity, and spatial distribution of drought events globally. In the coming decades, global warming is expected to continue to increase alongside a growing global population, placing excessive pressure on water resources and increasing the frequency of drought worldwide (Yang et al., 2026). Understanding this relationship is an essential context for examining how drought threatens water quantity and quality across hydrologic systems.

At the most fundamental level, extreme climate and adverse weather intensify droughts by altering precipitation patterns and atmospheric demand. Rising temperatures increase evapotranspiration rates, drawing moisture from soils and vegetation at accelerating rates, while simultaneously creating greater variability in when and how precipitation falls (Disasa et al., 2026). One of the more surprising findings in recent literature is that drought severity can intensify even in areas where total annual rainfall is rising. Research from South Korea shows that although overall rainfall is increasing, the concurrent rise in weather variability—characterized by greater fluctuations in rainfall and temperature—is leading to more severe and prolonged droughts. This development raises serious concerns about water security and highlights the urgency for a fundamental reassessment of current water management practices (Park et al., 2026). This precipitation paradox challenges traditional assumptions about water availability and highlights

the inadequacy of using total rainfall alone as a drought risk indicator. Critically, even when rainfall remains within the bounds of natural variability, the consequences of drought are becoming more severe due to the concurrent and strong increase in extreme heat (Arias et al., 2024).

The role of human activity in driving the drought trends has been well established. Analysis of drought conditions from severe rainfall deficit in southern Australia during the millennium drought (1995-2009) is attributed to anthropogenic climate change, with the Coupled Model Intercomparison Project Phase 5 (CMIP5) model results confirming a human-induced signal in the observed drying trend (Cai et al., 2014). Similarly, research on the extreme 2018 drought in the Netherlands concluded that approximately half of the observed trend could be attributed to human-induced climate change. However, climate models continue to underestimate the magnitude of the observed trend, pointing to remaining uncertainties in climate projections (Philip et al., 2020). Moreover, not all drought events are equally attributable to global warming. Analysis of the 2014 drought in California suggested that while a long-term warming trend may have slightly exacerbated conditions, the event was primarily driven by anomalously low winter precipitation rather than temperature alone, underscoring the continued role of natural precipitation variability in shaping individual drought events (Mao et al., 2015). These case studies collectively illustrate that while the fingerprint of anthropogenic forcing on drought is increasingly detectable, the relative contributions of climate change and natural variability remain context-dependent and geographically variable.

At a broader scale, hydrological studies have confirmed that the spatiotemporal characteristics of drought are shifting in response to warming across multiple regions. Research conducted in Iran found that the severity and frequency of future droughts are expected to worsen, particularly in warmer climates, across both meteorological and hydrological dimensions, underscoring the urgency of current water resource management to preserve these systems for future generations (Bayatavrkeshi et al., 2023). In East Asia, analysis of seasonal drought trends using the Standardized Precipitation Evapotranspiration Index (SPEI) revealed clear drying trends across Japan, Mongolia, and The Democratic People's Republic of Korea across different growing seasons, highlighting that drought dynamics vary not only spatially but also temporally across seasons and regions (Ali et al., 2024). Quantitative drought hazard assessments for South Korea using multiple drought indices (including the Standardized Precipitation Index (SPI), SPEI, and the Self-Calibrating Palmer Drought Severity Index (SC-PDSI)) confirmed that average drought severity is projected to intensify under future climate change scenarios, with higher drought frequency and occurrence corresponding to greater overall drought risk (Nam et al., 2015). Globally, severe droughts are projected to increase across many regions of the world, with Europe among the areas facing particularly significant intensification (Disasa et al., 2026; Mosley, 2015), and the Intergovernmental Panel on Climate Change (IPCC) has projected that these trends will pose considerable challenges to water availability for society, the environment, and ecosystems (Qiu et al., 2023).

Compounding these physical drivers—rising temperatures, increased evapotranspiration, altered precipitation patterns, and extreme heat events—are the growing pressures of human water demand and land-use change. Land-use decisions have further amplified this vulnerability; the conversion of cultivated lands to built-up areas reduces groundwater volumes, lowers water reserves in aquifers, and increases the extent and frequency of intense floods, all of which heighten exposure to drought (Azadi et al., 2018). In many regions, anthropogenic alteration of the hydrologic cycle has created conditions in which water shortages persist even during wet years, driven by a large and growing imbalance between water supply and demand (AghaKouchak et al., 2021). This situation blurs the distinction between drought driven by climate and water scarcity driven by humans, making it harder to identify a single cause of water stress. Whether drought intensification is primarily periodic, climate-driven, or human activity-driven in any given context remains an open and consequential question for water managers (Haile et al., 2020). What is clear, however, is that the combination of adverse weather, extreme climate, rising water demand, and land-use transformation is creating a trajectory in which drought events will become more frequent, more severe, and more consequential for the hydrologic resources on which both aquatic ecosystems and human communities depend.

The variability and persistence of drought conditions in the United States illustrate the complex and dynamic nature of drought described above. **Figure 4** shows the percentage of U.S. area affected by drought from 2000 to 2026, based on data from the National Integrated Drought Information System (NIDIS) and classified according to the U.S. Drought Monitor (USDM) intensity categories. The USDM characterizes drought severity across five levels: D0 (abnormally dry), D1 (moderate drought), D2 (severe drought), D3 (extreme drought), and D4 (exceptional drought), where higher categories reflect increasingly severe deficits in precipitation, soil moisture, and streamflow with correspondingly greater impacts on water supply, agriculture, and ecosystems. As shown in **Figure 4**, drought coverage across the contiguous United States has been highly variable over the study period, with notable peaks in 2002, 2013, 2022, 2023, 2025, and 2026, during which a substantial

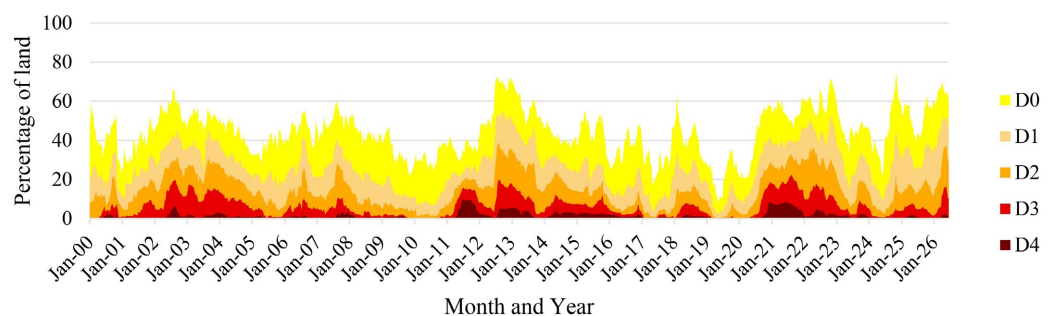


Figure 4. Percentage of U.S. area affected by drought by intensity category (D0 - D4) from 2000 to 2026. D0 = abnormally dry; D1 = moderate drought; D2 = severe drought; D3 = extreme drought; D4 = exceptional drought. Data sourced from the National Integrated Drought Information System (NIDIS) via the U.S. Drought Monitor (USDM).

proportion of the country experienced severe to exceptional conditions. This temporal variability reinforces the point that drought is not a static condition but rather a dynamic and recurring stress on water systems, with implications for both water quantity and quality that motivate the body of literature examined in this review.

4. Impacts of Drought on Surface and Ground Water Quantity

Drought significantly alters the hydrological processes that regulate water quantity and distribution within hydrologic systems. Its primary impacts include reduced surface water availability, groundwater depletion accompanied by delayed recharge, and the loss of hydrological connectivity among rivers, lakes, wetlands, and other water bodies. These fundamental hydrological changes subsequently drive a cascade of physical, chemical, and biological alterations, ultimately affecting the structure, function, and resilience of aquatic ecosystems. This section reviews empirical evidence documenting each mechanism across diverse hydrological settings.

The most immediate hydrological response to drought is the reduction of surface water availability. When rainfall is absent, soil moisture declines, surface runoff diminishes, and recharge to both surface and groundwater systems is curtailed (Bond et al., 2008). Surface runoff, interflow, and groundwater contribute to streamflow during wetter periods. However, during droughts, when these sources are limited, water bodies become increasingly dependent on slower, more vulnerable groundwater inputs to maintain streamflow (Van Loon, 2015). As a result, water levels in rivers, lakes, and reservoirs decline, reducing the total volume of water available within hydrologic systems and fundamentally altering their physical characteristics (Disasa et al., 2026).

This drought-surface water relationship has been empirically documented across diverse hydrological systems. In Iran, seasonal surface water exhibited marked sensitivity to drought variability between 2000 and 2021, with the most severe drought episodes: 2008 (SPEI: -1.92), 2014 (SPEI: -1.67), and 2010 (SPEI: -1.53), triggering immediate reductions in water availability (Kazemi Garajeh et al., 2024). These SPEI values correspond to severe to extreme drought conditions based on standard SPEI classification thresholds, where values between -1.50 and -1.99 indicate severe drought and values of -2.00 or below indicate extreme drought (McKee et al., 1993). Highland regions proved particularly vulnerable, with surface water areas declining from 175.3 km^2 in 2000 to a minimum of 111.7 km^2 in 2018 following sustained drought conditions. The catastrophic 2008 drought alone reduced highland water resources by 54.2 km^2 within a single year, demonstrating the rapid hydrological response to precipitation deficits. Even lowland systems, which maintained greater resilience through groundwater baseflow contributions, experienced significant declines from peak levels of $1,778.6 \text{ km}^2$ in 2019 during subsequent drought intensification in 2020-2021 (Kazemi Garajeh et al., 2024).

In southwest China, a six-year drought from 2008 to 2014 produced similarly dramatic impacts on surface water systems. Rainfall declined precipitously from 963.8 mm in 2007 to 786.3 mm in 2008, reaching a minimum of 496.8 mm in 2011,

with seasonal rainfall deficits during autumn 2009 to spring 2010 and summer 2011 exceeding 80 - 90% (Chen et al., 2024). These precipitation deficits translated directly into lake water losses: by 2012, the inundated area decreased by 12.88% compared to 2002, lake depth declined by 1.38 m relative to the pre-drought average of 7 m, and total water storage was reduced by approximately 21.6%. During the peak drought period (2009-2013), water storage averaged 17% below pre-drought levels (2000-2008). Notably, while rainfall patterns indicated drought recovery by 2014, water levels did not return to normal until 2015, illustrating the hydrological lag between meteorological recovery and surface water restoration (Chen et al., 2024).

Similarly, in South-East Australia, prolonged drought from 1993 to 2006 resulted in a 60% decrease in lake surface area across 28 studied lakes ($220 \times 10^6 \text{ m}^2$ reduction), with volumetric losses reaching $714 \times 10^6 \text{ m}^3$, representing an 80% decrease for lakes where detailed measurements were available (Tweed et al., 2009). These observations confirm that drought consistently reduces surface water availability across different topographic and climatic contexts, supporting the hypothesis that precipitation deficits directly translate to diminished water storage in rivers, lakes, and reservoirs.

Groundwater storage plays a critical buffering role during drought, moderating hydroclimatic variations in water availability and helping mitigate drought impacts on streamflow during dry periods (Hellwig et al., 2022). However, this buffering capacity is neither unlimited nor uniform. As surface moisture declines, the depletion of soil moisture storage reduces recharge to the groundwater system, leading to progressively declining groundwater levels over time (Van Loon, 2015). The rate at which surface water responds to drought varies considerably depending on catchment hydrogeology. Catchments with large dynamic groundwater storage tend to exhibit a slower surface water response to drought, while those dominated by fast groundwater flow pathways or limited storage respond more rapidly to drought conditions (Hellwig et al., 2022). This variability means that the hydrological signature of drought differs substantially across landscapes, complicating prediction and management efforts. In addition, groundwater systems may remain depleted for months or even years after meteorological drought has ended, meaning that the hydrological consequences of a single drought event can extend well beyond its visible duration (Bond et al., 2008).

The sustained nature of groundwater depletion during prolonged drought has been quantified using satellite-based gravity measurements. In California's Central Valley, Gravity Recovery and Climate Experiment (GRACE) data revealed a continuous decline in groundwater storage throughout the satellite record, with the monthly climatology never rising above zero. The Groundwater Drought Index documented two distinct periods of groundwater drought, with the recent drought beginning in 2012 exhibiting substantially greater severity compared to the earlier 2007-2011 event, demonstrating that successive drought episodes can progressively weaken groundwater system resilience (Thomas et al., 2017).

Similar patterns of accelerated depletion have been documented globally. In the Colorado River Basin during 2004-2013, groundwater accounted for 50.1 km^3 of

the total 64.8 km³ freshwater loss, with depletion rates of −5.6 km³/year far exceeding the combined losses from Lake Powell and Lake Mead. Depletion intensified over time, with rates in the upper basin increasing from −1.9 km³/year during 2004-2010 to −6.1 km³/year during 2010-2013 (Castle et al., 2014). In Iran, groundwater storage declined by approximately 74 km³ during 2002-2015 at a rate of 5.25 km³/year, with the Salt Lake basin, supporting over 26% of the country's population, losing 20 km³ alone, equivalent to 81% of total depletion in the U.S. High Plains aquifer during the severe 1976-1977 drought (Ashraf et al., 2021). These observations demonstrate that groundwater depletion during drought can reach magnitudes comparable to or exceeding surface water losses, fundamentally altering baseline water availability in affected regions.

Anthropogenic pressures further compound the depletion of groundwater resources during drought. Human consumption and irrigation withdrawals can significantly influence groundwater availability, particularly in regions already facing limited water supply, with documented differences in groundwater drought deficit and duration reported in areas subject to high human extraction rate (Vega-Briones et al., 2024). This feedback between human water demand and groundwater depletion mirrors the broader regional dynamic, in which anthropogenic alteration of the hydrologic cycle creates water shortages that persist even during wet years (AghaKouchak et al., 2021).

Beyond direct impacts on water availability, the depletion of surface and groundwater drives a progressive loss of hydrological connectivity, defined as the degree to which water, materials, and organisms can move freely through a landscape and its associated water bodies. In stream systems, drought causes the water body to become increasingly fragmented as flow diminishes, isolating pools and disconnecting reaches that would otherwise function as a continuous system (Lake, 2003). This fragmentation disrupts the movement of water, nutrients, sediments, and biota through the landscape, fundamentally altering the processing and transport of materials within and between hydrological systems. The magnitude of drought-induced losses in hydrological connectivity varies across basins but remains substantial. In the Colorado River Basin, streamflow declined by 19.3% on average during 2000-2014, with at least one-third of this decline attributed to climate-driven warming (Udall & Overpeck, 2017). As documented by Wang et al. (2025a), more frequent intermittent flows and reduced channel network connectivity in northeast Germany's Demnitzer Millcreek, illustrating the disruption of water exchange between surface and groundwater systems due to climate-driven drought.

Together, these findings show that drought does more than reduce the amount of water in hydrological systems; it fundamentally restructures the hydrological framework that sustains them. Water bodies become diminished in volume, fragmented in connectivity, and increasingly reliant on diminished groundwater and surface water reserves. Yet these hydrological shifts are not merely quantitative reductions; they actively reconfigure the physical, chemical, and biological characteristics that determine water quality. Declining surface water volumes concen-

trate pollutants. Reduced groundwater inputs alter baseflow chemistry. At the same time, fragmentation of hydrological connectivity disrupts nutrient retention, biogeochemical processing, and the movement of organisms and materials across the landscape. As a result, drought transforms not only the quantity of water available but also the nature of the water that remains.

Table 1 summarizes empirical evidence of drought-induced changes in water quantity across diverse hydrological settings, including surface water loss, groundwater depletion, and reduced streamflow, drawn from studies spanning Iran, China, Australia, United States, and Germany (2000-2025).

Table 1. Summary of drought-induced changes in water quantity across selected regions.

Region	Drought Period	Water Quantity Changes	Key Sources
Iran (Highland regions)	2000-2021 (peak events: 2008, 2010, 2014)	Surface water area declined from 175.3 km ² (2000) to a minimum of 111.7 km ² (2018). The 2008 drought alone reduced highland water resources by 54.2 km ² within a single year.	(Kazemi Garajeh et al., 2024)
Iran (Lowland regions)	2020-2021	Lowland surface water declined significantly from a peak of 1,778.6 km ² in 2019 during subsequent drought intensification in 2020-2021.	(Kazemi Garajeh et al., 2024)
Iran (National)	2002-2015	Groundwater storage declined by ~74 km ³ at a rate of 5.25 km ³ /year. The Salt Lake basin alone lost 20 km ³ (81% of total U.S. High Plains aquifer depletion during the severe 1976-1977 drought), despite supporting over 26% of Iran's population.	(Ashraf et al., 2021)
Southwest China	2008-2014 (six-year drought)	Inundated lake area decreased by 12.88% (vs. 2002); lake depth declined by 1.38 m relative to pre-drought average of 7 m; total water storage reduced by ~21.6%. During peak drought (2009-2013), storage averaged 17% below pre-drought levels. Water levels did not recover until 2015, one year after meteorological drought ended.	(Chen et al., 2024)
South-East Australia (28 lakes)	1993-2006 (prolonged drought)	Lake surface area decreased by 60% (220×10^6 m ² reduction). Volumetric losses reached 714×10^6 m ³ , representing an 80% decrease for lakes with detailed measurements.	(Tweed et al., 2009)
California (Central Valley)	2007-2011; 2012-present (at time of study)	Continuous decline in groundwater storage throughout GRACE satellite record; monthly climatology never rose above zero. Successive drought episodes progressively weakened groundwater system resilience.	(Thomas et al., 2017)
Colorado River Basin (USA)	2004-2013	Total freshwater loss of 64.8 km ³ , of which groundwater accounted for 50.1 km ³ . Groundwater depletion rate: -5.6 km ³ /year. Depletion intensified from -1.9 km ³ /year (2004-2010) to -6.1 km ³ /year (2010-2013) in the upper basin, far exceeding combined losses from Lake Powell and Lake Mead.	(Castle et al., 2014)

Continued

Colorado River Basin (USA)	2000-2014	Streamflow declined by 19.3% on average between 2000-2014. At least one-third of this decline attributed to climate-driven warming.	(Udall & Overpeck, 2017)
Northeast Germany (Demnitzer Millcreek)	2018-2022	More frequent intermittent flows and reduced channel network connectivity documented. Disruption of water exchange between surface and groundwater systems observed.	(Wang et al., 2025a)

5. Impacts of Drought on Water Quality

Drought affects water quality through a series of interrelated changes that extend well beyond simple reductions in water availability. As streamflow declines and water residence times increase, the physical, chemical, and biological properties of aquatic systems shift in ways that are often nonlinear, delayed, and context-dependent. This section examines these impacts across three interconnected domains. Section 5.1 addresses physical water quality impacts, including changes in water temperature, sediment dynamics, turbidity, and the concentration of dissolved solids. Section 5.2 turns to chemical impacts, covering nutrient cycling, dissolved oxygen depletion, pH shifts, and the mobilization of contaminants and heavy metals. Section 5.3 then explores biological impacts, focusing on microbial indicators, algal and cyanobacterial blooms, and the responses of invertebrate and fish communities to habitat loss and reduced connectivity. Taken together, these subsections demonstrate that a comprehensive understanding of drought's effects on water quality requires considering physical, chemical, and biological perspectives together, as each domain shapes and constrains the others.

5.1. Physical Water Quality Impacts

Drought fundamentally alters the physical characteristics of water bodies, triggering interconnected changes that impact the physical properties and quality of surface and ground water systems. As streamflow declines and water levels drop, one of the most immediate responses is the substantial increase in water temperature, driven by reduced thermal capacity and heightened sensitivity to atmospheric heating. These elevated temperatures coincide with dramatic shifts in sediment dynamics and turbidity, in which reduced flow initially limits erosion but creates conditions for sudden sediment pulses during intermittent rainfall events. The altered flow regime further disrupts the natural flushing capacity of river systems, constraining the transport and redistribution of accumulated materials throughout the catchment. Simultaneously, declining water volumes and intensified evapotranspiration concentrate dissolved materials, increasing electrical conductivity and salinity, and reshaping habitat conditions, particularly in irrigated and estuarine systems. Together, these physical transformations (elevated temperatures, altered sediment and turbidity patterns, reduced flushing capacity, and increased concentrations of dissolved solutes) lay the foundation for broader water-quality degradation, setting the

stage for chemical and biological impacts that compound drought's effects on ecosystems.

Reduced discharge lowers rivers' thermal capacity, making them more sensitive to atmospheric heat inputs (van Vliet et al., 2011). During dry, warm periods, water temperatures can increase substantially, sometimes reaching critical levels that can severely impact aquatic environments. These elevated temperatures can lead to a range of negative effects on the ecosystem, including stress on aquatic life, reduction in biodiversity, and disruption of natural processes. Moreover, higher water temperatures pose challenges for human water use, affecting agriculture, industry, and municipal water supplies. Understanding and managing these temperature fluctuations is vital to maintaining healthy ecosystems and ensuring sustainable water resources. Empirical evidence consistently shows that hydrological droughts are associated with elevated water temperatures, often accompanied by declines in dissolved oxygen (Ahmadi & Moradkhani, 2019; Graham et al., 2024). These temperature increases are further exacerbated in regions experiencing heatwaves and in highly managed or irrigated basins, where altered flow regimes and increased water withdrawals intensify warming trends (Graham et al., 2024; Vega-Briones et al., 2024).

In parallel, drought strongly modifies sediment dynamics and turbidity, though these responses are often nonlinear and context dependent. Reduced rainfall generally limits the erosive power of runoff, thereby reducing sediment yields during prolonged dry periods (Dunbar et al., 2010). However, drought also reduces vegetative cover and soil moisture, increasing landscape vulnerability to erosion when rainfall does occur. Consequently, intense storms during drought periods can generate disproportionately high sediment loads relative to the volume of runoff (Allen et al., 2011). This results in a paradox where sediment transport is limited during dry conditions but can increase sharply during intermittent flow events.

During drought conditions, reduced runoff and slower flow velocities allow suspended particles to settle more easily, often resulting in clearer water and lower turbidity. Turbidity often decreased during droughts in rivers and streams with no significant loading from point and agricultural non-point sources, due to disruption of catchment inputs (Mosley, 2015). For instance, studies in the Haraz Basin, Iran, documented Total Suspended Solids (TSS) concentrations ranging from 202 - 1,212 mg/L across both rainy and dry seasons, demonstrating substantial seasonal variability in suspended solids (Nasrabadi et al., 2016). Similar seasonal variability has been documented in the Colorado River Basin, where TSS and TDS concentrations varied significantly across months, seasons, and years, with agricultural practices, consumptive water use, snowmelt runoff, and increased evaporation contributing to these variations (Adjovu et al., 2023). While this might initially suggest an improvement in water quality, it is usually short-lived. As flow returns (following the end of a drought event), previously settled sediments can be rapidly disturbed and transported downstream, causing a sudden increase in turbidity. This resuspension reduces light penetration in the water column and can ultimately limit productivity, highlighting the transient and de-

ceptive nature of improved clarity during dry periods (Ahmadi & Moradkhani, 2019). Since turbidity directly influences light availability within the water column, it plays a critical role in regulating physical habitat conditions and ecosystem functioning (Ade et al., 2021).

Finally, drought alters flow pathways and reduces natural flushing in catchments, further reinforcing physical water-quality changes. Limited water flow and altered hydrological connectivity constrain sediment and other material movement, while the absence of regular rainfall events reduces the system's ability to transport and redistribute accumulated particles (Clark et al., 2017). For instance, research done during the megadrought period (2010-2017) in Chile's Itata River Basin showed substantial reductions in sediment discharge due to decreased fluvial transport capacity (Méndez-Freire et al., 2022). The basin outlet recorded a dramatic 67.2% decrease in sediment discharge. Declining from 491,326 tons/year pre-drought to 161,139 tons/year during the megadrought.

Following these changes in sediment and turbidity dynamics, drought also alters the concentration of dissolved materials in ways closely linked to physical hydrological processes. As water volumes decrease and evapotranspiration intensifies, the remaining water becomes progressively concentrated, leading to higher dissolved ion concentrations and, consequently, higher electrical conductivity (EC) and salinity in rivers, lakes, and estuaries (Bond et al., 2008; Graham et al., 2024). While EC is commonly treated as a physical water-quality parameter, it primarily reflects the concentration of dissolved ions and is therefore strongly influenced by both physical and chemical processes. Empirical evidence supports this pattern, as the increases in salinity (indirectly indicated by EC) during drought are most pronounced in irrigated regions, where agricultural return flows introduce additional solutes into already reduced water bodies (Graham et al., 2024). In estuarine systems, reduced freshwater inflows during drought further enhance these effects by allowing saltwater intrusion to extend farther inland, altering salinity gradients and reshaping habitat conditions (Wetz & Yoskowitz, 2013).

These changes highlight the tightly coupled, nonlinear interactions among hydrology, vegetation, and erosion processes under drought conditions, in which small shifts in one component can amplify physical responses across the system (Dunbar et al., 2010). The physical alterations driven by drought, including elevated water temperatures, disrupted sediment dynamics, modified turbidity patterns, and increased concentrations of dissolved materials, fundamentally reshape hydrologic systems and create conditions that propagate into the chemical and biological domains. Rising temperatures and reduced flows create an environment more susceptible to chemical transformations, while increased ion concentrations and altered sediment transport modify the chemical composition of water bodies. These physical changes do not happen in isolation; instead, they interact with and enhance chemical processes like nutrient cycling, oxygen levels, and contaminant behavior. Additionally, the altered physical conditions have a direct impact on biological communities, influencing organism metabolism, species distribution, and overall eco-

system productivity. The following section examines how these physical stressors translate into chemical and biological impacts on water quality, revealing the deeply interconnected nature of drought's effects on aquatic ecosystems.

5.2. Chemical Water Quality Impacts

Drought has profound effects on the chemical composition of freshwater systems, altering nutrient dynamics, dissolved oxygen levels, pH, and pollutant concentrations. These chemical changes are closely linked to alterations of hydrological systems and persist well beyond the drought period itself. As water volumes decrease and flow paths shift, the levels of dissolved and suspended materials in hydrological systems change significantly through both passive concentration and active biogeochemical transformations triggered by altered temperature, oxygen, and redox conditions. Critically, the relationship between drought and chemical water quality is complex and often counterintuitive. Reduced catchment loading does not guarantee improved water quality, as point sources become proportionally more significant and internal processes drive further degradation. The effects of drought extend into recovery phases, when accumulated nutrients and contaminants are flushed through systems during rewetting events. These chemical responses have serious implications for both ecosystem health and human water use, setting the stage for biological impacts across all levels of aquatic communities.

Drought-induced dynamics in nutrient loadings, such as nitrogen and phosphorus, are complex and system-dependent. In rivers and streams, reduced runoff generally reduces allochthonous nitrogen and phosphorus loading from catchments, as overland flow and soil leaching decline (Qiu et al., 2023). This study confirmed that hydrological drought significantly reduces nutrient loads, with surface runoff identified as a key external factor affecting nutrient levels transport. However, the relationship between drought and nutrient concentrations is non-linear. Even as total nutrient loads decrease, concentrations within the water column can increase as dilution capacity is lost, a process that is particularly pronounced in lakes and reservoirs, where point-source inputs such as wastewater effluent and mine drainage become proportionally more significant relative to reduced inflows (Sun et al., 2025). This dynamic means that drought can simultaneously reduce nutrient inputs at the catchment scale while increasing nutrient concentrations within water bodies, leading to localized eutrophication even as overall loading declines. Research from the Poyang Lake in China that demonstrates this spatial complexity (Mao et al., 2025), by evaluating different water-quality indices, the heterogeneity across the lake system becomes clear. This highlights that drought-driven chemical deterioration is not uniform across a water body, and that assessment frameworks must account for variability within the system.

Drought can substantially alter nitrogen cycling within catchments. Meta-analysis of 148 publications covering 1,815 sampling points worldwide found that drought increased mineral nitrogen content by 31% while reducing nitrogen mineralization rates by 5.7% and nitrification rates by 13.8% (Deng et al., 2021). These

changes in terrestrial nitrogen cycling may increase the potential for nitrogen accumulation within catchments and subsequently influence nitrogen transport to aquatic systems when hydrological connectivity is restored. As noted by (Disasa et al., 2026), severe droughts projected to increase across Europe may reduce nitrogen retention in catchments, lower the groundwater table, and in turn worsen nitrate pollution and threaten drinking water quality. The lack of regular flushing by rainfall allows solutes like nitrate to accumulate in catchment soils and shallow groundwater, creating a pulse of elevated concentrations when flow eventually returns (Clark et al., 2017).

Field experiments in degraded grasslands have demonstrated how drought can alter terrestrial conditions relevant to nutrient cycling and transport. Moderately degraded systems experiencing 80% decreases in soil moisture and 78% declines in aboveground biomass under drought conditions, while nitrogen addition failing to mitigate these effects (Li et al., 2023). Such changes in soil moisture and vegetation can modify nutrient retention and mobilization within catchments, potentially affecting the transport of nitrogen to downstream aquatic systems. Post-drought flushing of accumulated nutrients can lead to unpredictable deterioration in water quality, especially in agricultural catchments where nitrogen is still applied during dry periods.

Similarly, phosphorus dynamics exhibit complex responses to drought, with both concentration effects and post-drought flushing creating water-quality challenges. During drought periods, the influence of agricultural land use on phosphorus loads is masked, but post-drought rainfall exacerbates its impact on phosphorus loading (Lisboa et al., 2020). Understanding these dynamics requires consideration of phosphorus speciation in hydrologic systems, including soluble reactive phosphorus (SRP), which is readily bioavailable to algae and aquatic plants, dissolved organic phosphorus (DOP), and particulate phosphorus (PP), with their sum constituting total phosphorus (TP). During extended dry periods when external nutrient inputs cease, phosphorus concentrations in water bodies increase primarily through the concentration of autochthonous nutrients as water volume declines, rather than from new inputs (Cavalcante et al., 2018).

The frequency of high phosphorus concentration events is projected to escalate dramatically under climate change scenarios, with modeling of the River Trent (UK) indicating that days exceeding 1 mg L^{-1} phosphorus could increase from 20 days annually under baseline conditions to 40 days in the near future and 70 days in the far future, driven by reduced flows and diminished dilution capacity (Bussi & Whitehead, 2020). Like nitrogen, the timing of post-drought rainfall is critical in agricultural watersheds, as the first storm events after drought can mobilize nutrients from soils and accumulated biomass, severely degrading water quality, particularly in areas where land use amplifies nutrient export (Disasa et al., 2026).

Dissolved oxygen (DO) is another critical chemical parameter severely impacted by drought. Reduced DO concentrations during drought events are driven by multiple concurrent mechanisms: elevated water temperatures reduce oxygen

solubility; increased stratification in lakes and reservoirs restricts oxygen transfer from surface to deeper waters; and elevated microbial decomposition of organic matter concentrated in reduced water volumes exerts significant oxygen demand (Ahmadi & Moradkhani, 2019; Mosley, 2015). As documented by Ahmadi & Moradkhani (2019), DO degraded consistently across water quality monitoring stations during detected droughts. The thermal dimension of this process is particularly important under compound drought-heatwave conditions, which are expected to become more intense and frequent under climate change. Extreme low-flow conditions increase the sensitivity of river water temperature to solar radiative energy inputs by reducing flow depths, flow velocities, and the overall thermal buffering capacity of watercourses, meaning that drought and heatwaves interact to produce temperature extremes that neither stressor would generate alone (White et al., 2023). In the hypolimnion of lakes and reservoirs, thermal stratification (intensified by drought) can produce anoxic conditions that further mobilize phosphorus from sediments, creating internal nutrient loading that persists even after surface inputs decline (Mosley, 2015). These hypoxic and anoxic conditions are among the most harmful chemical effects of drought.

Organic matter dynamics also shift substantially under drought. Reduced runoff reduces the transport of allochthonous (terrestrially derived) organic carbon into water bodies (Humphries & Baldwin, 2003). Simultaneously, increased algal production in nutrient-enriched, thermally stratified water bodies can elevate autochthonous organic matter concentrations. The decomposition of this accumulated organic material further depletes dissolved oxygen and contributes to sediment oxygen demand, creating a self-reinforcing cycle of chemical deterioration (Mosley, 2015). These drought-induced effects were demonstrated in the Inaouene River basin in Morocco, where successive drought periods led to pronounced degradation of water quality across multiple parameters. During a low-rainfall hydrological cycle, organic matter concentrations increased substantially, with Biochemical Oxygen Demand (BOD₅) rising by 41.53% and Chemical Oxygen Demand (COD) by 37.08% compared to the previous cycle (Sghiouer et al., 2024). This organic matter accumulation coincided with a 46.26% reduction in dissolved oxygen and a 9.39% increase in water temperature, exemplifying the interconnected nature of drought impacts on the chemistry of water.

Building on the role of organic matter transformations during drought, changes in pH represent another critical chemical response that reflects both concentration effects and underlying geochemical processes. Reduced water levels and prolonged sediment exposure can fundamentally alter acid-base dynamics in hydrological systems. One of the most striking mechanisms occurs when previously submerged, sulfur-rich sediments are exposed to oxygen during drought. As documented by Mosley et al. (2014), the oxidation of pyrite in these exposed sediments can generate sulfuric acid, leading to extreme acidification upon rewetting. In the Lower Lakes of the Murray-Darling Basin, this process resulted in sustained surface water pH values as low as 2 - 3, far below ecological guideline ranges (pH

6.5 - 9.0). Acidification affected a measurable portion of the system, with approximately 21.7 km² of surface water falling below pH 6.5. These conditions were not only chemically extreme but also ecologically hazardous, as they were accompanied by elevated concentrations of dissolved metals such as aluminum, iron, and manganese, which become more soluble at low pH.

In contrast to such severe acidification events, other drought-impacted systems may exhibit more moderate or variable pH responses depending on local hydrology and biogeochemical conditions. As indicated by [van Vliet & Zwolsman \(2008\)](#), droughts can indirectly influence pH by altering temperature, nutrient concentrations, and eutrophication processes. Reduced flows and higher temperatures in the Meuse River during the 1976 and 2003 droughts contributed to overall deterioration in water quality, including enhanced algal productivity and altered chemical balances. While pH was not reported to reach extreme acidic levels as in the Murray-Darling case, these interacting factors can still drive fluctuations in pH through processes such as photosynthesis and respiration, which respectively increase and decrease pH. Overall, the direction and magnitude of pH change during drought are highly context-dependent, but both acidification from sediment oxidation and biologically mediated shifts linked to eutrophication highlight pH's sensitivity as an integrative indicator of drought-induced changes in water quality.

Finally, drought-driven changes in flow pathways alter the transport and accumulation of pollutants. Drought can affect concentration-discharge relationships by limiting water throughput and altering flow paths through dry soils, while the absence of regular rainfall flushing allows solutes to accumulate in catchments ([Clark et al., 2017](#)). These accumulated contaminants, such as heavy metals (e.g., arsenic, lead), pesticides (e.g., nitrates, phosphorus), nutrients, and other agrochemicals, are then released during post-drought flow events, potentially exposing hydrologic, aquatic ecosystems, and drinking water sources to higher levels of contaminant loads. The reduced dilution capacity and the relative increase in point-source discharges can lead to chemical or microbial contamination and toxic cyanobacterial blooms, rendering water unsuitable for human consumption ([Sun et al., 2025](#)). The chemical consequences of drought, therefore, extend beyond the drought period itself into recovery phases, underscoring the importance of long-term monitoring across the full drought cycle.

These shifts in contaminant transport and accumulation are particularly relevant for heavy metals, which are persistent environmental contaminants that can accumulate in soils and sediments and are influenced by changing hydrological and biogeochemical conditions. Heavy metals are defined as elements with relatively high atomic weight and density that persist in the environment and are not readily degraded ([Islam & Sandhi, 2023](#)). While certain metals, such as zinc (Zn), copper (Cu), cobalt (Co), nickel (Ni), molybdenum (Mo), and manganese (Mn), are essential micronutrients at low concentrations but can adversely affect biological and physiological processes when present at elevated levels. Drought can alter the conditions that regulate the retention and mobility of these metals within

catchments. Reduced water availability and increased evaporation can concentrate dissolved constituents, while changes in redox conditions and sediment chemistry may promote the mobilization of metals from soils and sediments (Islam & Sandhi, 2023). These changes can increase the potential for metals to be transported to aquatic systems when hydrological connectivity is restored, potentially contributing to elevated metal concentrations and associated ecological risks during drought and subsequent periods of hydrological recovery.

Recent evidence highlights the magnitude of these changes under combined heat and drought conditions. The summer heat and drought significantly increased heavy metal concentrations in sediment pore water across estuarine wetlands, with overall increases of 3.1 - 3.5 times compared to pre-drought conditions (Luo et al., 2025). Individual heavy metal concentration increases were substantial, including arsenic (As) by 441%, manganese (Mn) by 672%, iron (Fe) by 197%, and cobalt (Co) by 357%. These changes were linked to altered redox dynamics, particularly hypoxic conditions that promote metal dissolution and limit the formation of stable oxidation zones. Spatial variability was also observed, with higher concentrations in tidal flats, mangrove wetlands, and tidal creeks compared to aquaculture ponds. Collectively, these findings demonstrate that drought not only concentrates heavy metals but actively drives their mobilization through biogeochemical transformations, amplifying risks to aquatic ecosystems and water quality.

The chemical effects of drought on freshwater systems are both diverse and interconnected. Nutrient dynamics shift in complex ways, with reduced catchment loading often accompanied by increased concentrations within water bodies as dilution capacity declines and point sources become proportionally more significant. Nitrogen and phosphorus cycling are disrupted, with accumulated nutrients in soils and sediments creating potential for severe water quality deterioration during post-drought flushing events. Dissolved oxygen concentrations decline through multiple mechanisms, including elevated temperatures, increased stratification, and enhanced microbial decomposition of accumulated organic matter, with compound drought-heatwave conditions intensifying these effects. pH can shift to extreme values through processes such as pyrite oxidation in exposed sediments, while heavy metal concentrations increase substantially through both concentration effects and altered redox conditions that enhance metal mobilization from sediments. The effects of drought persist into recovery phases, when accumulated nutrients and contaminants are flushed through systems during rewetting events. These chemical transformations create conditions that directly affect aquatic organisms and communities, as discussed in the following section on biological effects.

5.3. Biological Water Quality Impacts

Hydrologic and aquatic ecosystems respond to drought not only through physical and chemical shifts but also through significant biological and ecological disturbances that can modify their structure and function at multiple levels. As water availability declines, organisms experience changes in habitat availability, water quality, temperature, oxygen conditions, and resource distribution, all of which

influence survival, reproduction, and species interactions. Biological responses to drought can be observed across a wide range of aquatic communities, beginning with changes in microbial water quality and fecal indicator bacteria, followed by shifts in primary producers such as phytoplankton, periphyton, and macrophytes. These changes can promote harmful algal blooms and alter nutrient and oxygen dynamics. Drought also affects higher trophic levels, including aquatic invertebrates and fish, by reducing habitat connectivity, simplifying habitats, and disrupting ecological interactions and food webs. Together, these responses demonstrate how drought functions as a broad ecological disturbance capable of reshaping freshwater ecosystems long after hydrological conditions recover.

The combined biological responses to drought highlight its role as a major ecological disturbance in freshwater systems. By altering species composition, habitat connectivity, and ecological interactions, drought can produce long-lasting effects on ecosystem stability and function, emphasizing the need to understand these impacts under a changing climate.

Drought can influence fecal coliform and other fecal indicator bacteria in surface waters, with changes depending on land use, hydrological conditions, and temperature. Reduced water levels and runoff during drought can alter microbial water quality by affecting reservoir mixing, transport pathways, and environmental factors such as DO, turbidity, and pH (Partyka et al., 2018). The response of fecal coliform bacteria varies across hydrological systems and is strongly influenced by local watershed and reservoir conditions. Several studies reported lower fecal coliform concentrations during drought conditions because reduced rainfall limits the transport of bacteria from agricultural lands and urban surfaces into streams and reservoirs. Using the Soil and Water Assessment Tool (SWAT) model in the Big Sunflower River Watershed, research found that reduced rainfall decreased the wash-off of fecal coliform bacteria (FCB) from soils, leading to lower bacterial concentrations in surface waters (Dakhlalla & Parajuli, 2020). The study also showed that even small increases in watershed temperature increased bacterial die-off rates and further reduced FCB concentrations. Their model simulations demonstrated that FCB concentrations were sensitive to both rainfall and temperature changes, with streamflow simulations producing R^2 values between 0.64 and 0.77 and FCB simulations producing R^2 values between 0.56 and 0.60. Large-scale global analyses support these findings. A global assessment of drought and heatwave impacts on water quality was conducted across 314,046 monitoring stations worldwide between 1980 and 2021 (Graham et al., 2024). The authors reported that median fecal coliform concentrations in rural rivers decreased from 130 cfu/100mL under normal conditions to 100 cfu/100mL during droughts, representing a 23% decline. Under combined drought and heatwave conditions, concentrations decreased further to 96 cfu/100mL, a 26% reduction. In urban rivers, median fecal coliform concentrations decreased from 260 cfu/100mL to 190 cfu/100mL during droughts and to 170 cfu/100mL during compound drought and heatwave events, corresponding to reductions of 27% and 34%, respectively. The

study suggested that lower runoff inputs and greater bacterial decay at higher water temperatures were the primary drivers of these declines.

Primary producers such as phytoplankton (cyanobacteria, diatoms, etc.), periphyton (algae, bacteria, fungi), and macrophytes are often the first to respond to drought conditions. In lakes and reservoirs, higher temperatures, stronger thermal stratification, increased nutrient concentrations, and reduced flushing create ideal conditions for phytoplankton growth, particularly cyanobacteria. Many studies report significant increases in chlorophyll and algal biomass during drought periods (Mosley, 2015). This pattern is supported by Wetz & Yoskowitz (2013), who found a consistent link between extreme drought and higher phytoplankton abundance across a wide range of systems. Similarly, studies in Texas reservoirs showed that reduced rainfall, elevated conductivity, and increased nitrogen concentrations during drought promoted higher chlorophyll-a levels and favored cyanobacterial species such as *Aphanizomenon*, indicating increased risk of harmful algal blooms (Gámez et al., 2019). These blooms are more than just a visual problem; they can release toxins, including cyanotoxins (Pal et al., 2020; Park et al., 2017), as well as hepatotoxins and neurotoxins, which are dangerous to humans, livestock, and wildlife. They also disrupt oxygen levels through respiration and block the light that other aquatic plants need, altering the environment many organisms rely on. Harmful algal blooms often become more frequent and last longer during droughts, fueled by higher temperatures and stronger stratification, effects that can be hard to reverse even after rainfall resumes (Mosley, 2015).

Invertebrates, including insects, worms, crustaceans, and mollusks, are highly sensitive to physical changes that drought brings to streams and rivers. Reduced flow leads to lower water velocity, shallower depths, and narrower wetted channels, while also increasing fine sediment deposition and altering temperature and water chemistry (Dewson et al., 2007). As habitats shrink and become more uniform, species richness often declines. The loss of habitat area and changes in food resources influence how organisms behave and interact, and these effects can spread through the entire community. A long-term study across 179 sites (Sarremejane et al., 2024), showed that communities already affected by poor water quality, altered flows, and land-use pressures were more vulnerable to drought and recovered more slowly. Sites influenced by water abstraction showed weaker recovery, while those with riparian vegetation recovered more quickly, highlighting how human pressures shape ecological outcomes during and after drought.

Fish communities face some of the most acute biological challenges imposed by drought, because they require water not just for physiological function but for movement, foraging, spawning, and the thermal and oxygen conditions that their physiology can tolerate. As reviewed by Lennox et al. (2019), freshwater fish responses to drought globally. They found that changes in temperature and precipitation reduce flows, shift the energy dynamics of hydrology systems, alter habitat features, and disrupt both lateral and longitudinal connectivity, ultimately affecting the survival, reproduction, and persistence of fish populations. Similarly, extreme drought has been reported to reduce fish abundance, biomass, and biodi-

versity, while altering community composition. Species with specialized habitat or flow requirements declined, whereas some planktivorous, herbivorous, and detritivorous fishes increased in relative abundance (Wetz & Yoskowitz, 2013).

Evidence from estuarine systems further demonstrates that drought impacts are often species-specific. In the Mondego Estuary (Portugal), a severe drought between 2003 and 2005 was associated with reduced fish production and lower diversity, with the greatest declines observed in *Dicentrarchus labrax*, *Platichthys flesus*, and *Pomatoschistus minutus* (Dolbeth et al., 2008). The authors suggested that elevated temperatures, salinity changes, and reduced freshwater discharge negatively affected egg and larval development, recruitment success, and food availability. Reduced river discharge may also weaken the chemical cues that larvae use to locate estuaries, further limiting juvenile recruitment. An important but sometimes overlooked factor in fish survival during drought is the availability of refugia. These are areas that retain water, cooler temperatures, or sufficient oxygen when surrounding conditions become unfavorable (Lennox et al., 2019). Earlier work showed that the presence of refugia can determine whether populations persist or disappear during drought (Magoulick & Kobza, 2003). Features such as groundwater-fed pools, deep stream sections, and spring-fed areas can provide critical shelter. However, when streams become fragmented due to declining flow, access to these refuges is often lost.

Overall, these biological responses demonstrate that drought places freshwater ecosystems under substantial ecological stress by simultaneously altering water quality, habitat availability, species interactions, and ecosystem connectivity. The combined effects of habitat contraction, declining environmental quality, disrupted food webs, and slow biological recovery can reduce ecosystem resilience and push aquatic communities toward ecological thresholds from which recovery may be difficult. Human activities such as water abstraction, land-use change, pollution, and flow regulation often intensify these impacts, increasing the vulnerability of already stressed systems. As emphasized by Sun et al. (2025), understanding how climate-driven drought interacts with existing anthropogenic pressures is essential for predicting future ecological change.

Table 2 summarizes the water quality parameters examined in this review, organized by physical, chemical, and biological category. Across all three domains, drought consistently disrupts key water quality indicators, though the direction, magnitude, and timing of effects vary considerably by parameter, system type, and local conditions.

Table 2. Summary of drought-induced effects on physical, chemical, and biological water quality parameters.

Category	Parameter	Drought-Induced Effects	Key Sources
Physical	Water Temperature	Reduced discharge lowers thermal capacity, making water more sensitive to atmospheric heat. Temperatures increase substantially during dry, warm periods, often accompanied by declines in dissolved oxygen. Effects are intensified in irrigated basins and during compound drought-heatwave events.	(Adjovu et al., 2023; Graham et al., 2024; van Vliet et al., 2011; Vega-Briones et al., 2024; White et al., 2023)

Continued

Physical	Sediment Dynamics	Reduced rainfall limits erosive power and sediment yields during dry periods. However, drought reduces vegetative cover and soil moisture, so intense storms during drought generate disproportionately high sediment loads. Post-drought rewetting causes sudden resuspension and downstream sediment pulses.	(Allen et al., 2011; Dunbar et al., 2010; Méndez-Freire et al., 2022)
	Turbidity	Slower flow velocities during drought allow suspended particles to settle, producing clearer water and lower turbidity in rivers without significant point-source or agricultural inputs. However, turbidity increases sharply when flow returns, reducing light penetration and limiting aquatic productivity.	(Ade et al., 2021; Ahmadi & Moradkhani, 2019; Mosley, 2015; Nasrabadi et al., 2016)
	Flushing Capacity	Limited water flow and altered hydrological connectivity constrain sediment and material movement. Absence of regular rainfall reduces the system's ability to transport and redistribute accumulated particles. Demonstrated by a 67.2% decrease in sediment discharge in Chile's Itata River Basin during the 2010-2017 megadrought.	(Ade et al., 2021; Clark et al., 2017)
	EC and Salinity	As water volumes decrease and evapotranspiration intensifies, dissolved ion concentrations increase, raising EC and salinity. Effects most pronounced in irrigated regions. In estuarine systems, reduced freshwater inflows allow saltwater intrusion to extend farther inland, altering salinity gradients and habitat conditions.	(Bond et al., 2008; Graham et al., 2024; Méndez-Freire et al., 2022)
Chemical	Nutrients (Nitrogen & Phosphorus)	Reduced runoff lowers allochthonous nutrient loading, but concentrations within water bodies can increase as dilution capacity declines and point sources become proportionally more significant. Post-drought flushing mobilizes accumulated nutrients from soils, causing severe deterioration in agricultural catchments. High-phosphorus events projected to increase from 20 to 70 days/year under future climate scenarios.	(Bussi & Whitehead, 2020; Cavalcante et al., 2018; Clark et al., 2017; Deng et al., 2021; Disasa et al., 2026; Lisboa et al., 2020; Mao et al., 2015; Qiu et al., 2023; White et al., 2023)
	DO	DO declines through multiple concurrent mechanisms: elevated temperatures reduce oxygen solubility; increased stratification restricts oxygen transfer to deeper waters; and microbial decomposition of concentrated organic matter exerts significant oxygen demand. Thermal stratification intensified by drought can produce anoxic hypolimnion conditions in lakes and reservoirs.	(Mosley et al., 2014; van Vliet & Zwolsman, 2008; White et al., 2023)
	pH	Drought can drive extreme acidification when exposed sulfur-rich sediments oxidize (pyrite oxidation), producing sulfuric acid upon rewetting. In the Murray-Darling Basin Lower Lakes, this resulted in sustained pH values of 2 - 3, affecting ~21.7 km ² of surface water. Other systems show moderate pH fluctuations linked to eutrophication-driven photosynthesis and respiration dynamics.	(Mosley et al., 2014; van Vliet & Zwolsman, 2008)
	Organic Matter (BOD and COD)	Reduced runoff decreases allochthonous organic carbon inputs, but increased algal production in thermally stratified, nutrient-enriched water bodies elevates autochthonous organic matter. Decomposition depletes DO and increases sediment oxygen demand. Demonstrated in Morocco's Inaouene River Basin: BOD ₅ rose 41.53% and COD rose 37.08% during low-rainfall cycles.	(Humphries & Baldwin, 2003; Mosley, 2015; Sghiouer et al., 2024)

Continued

Chemical	Heavy Metals	Reduced water volumes and evaporation concentrate dissolved metals. Altered redox and sediment chemistry enhance metal release from soils and sediments. Under combined heat and drought, heavy metal concentrations in estuarine pore water increased 3.1 - 3.5× overall, with As increasing 441%, Mn 672%, Fe 197%, and Co 357%.	(Islam & Sandhi, 2023; Luo et al., 2025)
	Pollutant and Contaminant Transport	Drought alters concentration-discharge relationships, limiting water throughput and allowing solutes (heavy metals, pesticides, nutrients, agrochemicals) to accumulate in catchments. Accumulated contaminants are released during post-drought flow events, elevating contaminant loads in aquatic ecosystems and drinking water sources.	(Clark et al., 2017; Sun et al., 2025)
	Harmful Algal Blooms (Cyanotoxins)	Reduced dilution capacity and relative increase in point-source discharges can trigger toxic cyanobacterial blooms, releasing cyanotoxins, hepatotoxins, and neurotoxins. Blooms disrupt oxygen levels and block light, rendering water unsuitable for human consumption. Blooms often persist after rainfall resumes due to stratification and nutrient loading.	(Mosley, 2015; Pal et al., 2020; Park et al., 2017; Sun et al., 2025)
Biological	Fecal Indicator Bacteria	Reduced rainfall limits washoff of fecal coliform bacteria (FCB) from agricultural and urban surfaces, generally decreasing concentrations during drought. Globally, rural river FCB decreased 23% during drought and 26% during compound drought-heatwave events; urban rivers showed 27 - 34% decreases. Higher temperatures increase bacterial die-off rates.	(Dakhlalla & Parajuli, 2020; Graham et al., 2024; Partyka et al., 2018)
	Phytoplankton, Periphyton and Cyanobacteria	Higher temperatures, stronger thermal stratification, increased nutrient concentrations, and reduced flushing create ideal conditions for phytoplankton growth, particularly cyanobacteria. Studies in Texas reservoirs found drought promoted higher chlorophyll-a levels and favored cyanobacterial species. Harmful algal blooms become more frequent and longer-lasting during drought.	(Gámez et al., 2019; Mosley, 2015; Sun et al., 2025)
	Aquatic Invertebrates	Reduced flow causes lower velocities, shallower depths, narrower wetted channels, finer sediment deposition, and altered temperature and chemistry, leading to declines in species richness. Communities already stressed by poor water quality and land-use pressures recover more slowly; riparian vegetation facilitates recovery.	(Dewson et al., 2007; Sarremejane et al., 2024)
	Fish Communities	Drought reduces flows, shifts energy dynamics, alters habitat features, and disrupts lateral and longitudinal connectivity, affecting survival, reproduction, and persistence. Extreme drought reduces fish abundance, biomass, and biodiversity. Species with specialized habitat or flow requirements decline. Loss of refugia due to stream fragmentation limits population persistence.	(Dolbeth et al., 2008; Lennox et al., 2019; Magoulick & Kobza, 2003; Sun et al., 2025)

6. Human Activities and Land-Use Influences on Drought Impacts

While drought is mainly a climate phenomenon, land-use patterns and human activities greatly influence its impact on water quality, often aggravating related issues. Land use refers to how land is shaped and managed for activities such as farming, urban growth, forestry, and industry. Human activities include actions such as water demand, irrigation, fertilizer use, groundwater extraction, wastewater disposal, and urban sprawl. Although related, land use refers to the overall organization of landscapes, while human activities are the specific processes that alter water systems'

hydrology, chemistry, and ecology. Collectively, these factors can change natural flow patterns, reduce groundwater recharge, increase pollution, and worsen water shortages during droughts. Consequently, distinguishing between natural and human-caused drought becomes harder. These combined influences can diminish water supply, accelerate the buildup of pollutants, and weaken the resilience of aquatic ecosystems during extended dry periods.

Human pressures can also increase the vulnerability of water-supply systems to drought, particularly as water demand grows and climate change intensifies drought risk. A global assessment of approximately 5,600 potable water supply utilities found that unsustainable or disrupted water supply already affects an average of 15% of utilities and could increase by 30 - 45% under future climate and demand scenarios, highlighting the growing challenge of maintaining drought-resilient water supplies (Becher et al., 2024). The study further demonstrated that although adaptation measures could substantially reduce future drought risk, financial constraints may limit their implementation, leaving water utilities increasingly exposed to climate-related pressures. These pressures are particularly evident in agricultural systems, where high water demand and intensive land management can amplify the effects of drought on both water availability and quality.

Agriculture is both a major consumer of water and a significant source of water quality impairment during drought. In the Netherlands, large precipitation shortfalls, declining water quality, and reduced water availability together impacted crop yields and grassland productivity, while simultaneously degrading the quality and quantity of surface waters used for drinking water, recreation, and natural ecosystems (Philip et al., 2020). In irrigated agricultural regions, drought triggers increased irrigation withdrawals from already-stressed surface and groundwater sources, accelerating depletion and intensifying the concentration of agricultural chemicals in remaining water bodies (Graham et al., 2024). As confirmed by Vega-Briones et al. (2024), anthropogenic activities (such as irrigation) can significantly influence groundwater resources in areas with limited water availability, thereby exacerbating groundwater drought duration and deficit compared to purely natural scenarios. Beyond irrigation, other agricultural land-management practices can further modify drought impacts; for example, combined drought and grazing pressures have been shown to reduce ecosystem resistance and alter post-drought recovery, with responses varying according to vegetation characteristics (Ruppert et al., 2015). Similarly, changes in land cover resulting from human land-management activities can modify vegetation responses to drought, with increased forest cover shown to improve vegetation drought resistance and reduce vulnerability in the Loess Plateau (Ding et al., 2021).

Agricultural nutrient management interacts with drought in ways that can produce significant downstream impacts on water quality. Water quality parameters, including nutrient concentrations, correlate with water level, reservoir inflow, and air temperature, variables closely linked to drought conditions (Lin et al., 2023). Critically, each reservoir studied has been shown to respond differently to changes

in nutrient levels, depending on variations in inflow and catchment pollution patterns, underscoring that assessing the potential impacts of human activities, such as different fertilization scenarios, is essential for understanding drought-nutrient interactions (Lin et al., 2023). Soil moisture availability during drought determines whether agricultural areas can be irrigated from surface or groundwater sources, effectively disconnecting soil moisture from precipitation in managed agricultural systems, but increasing pressure on water bodies as irrigation demand rises (Philip et al., 2020).

In addition to nutrient enrichment, drought also alters the environmental behavior of agrochemicals and pesticides in agricultural systems, increasing their persistence and changing their transport pathways to surface and groundwater. Drought conditions have been reported to inhibit degradation processes and promote the retention of agrochemicals and their transformation products in soils, especially when moisture levels are low (Nagesh et al., 2024). Although reduced runoff and leaching during drought may temporarily decrease pesticide transport to rivers, accumulated residues can remain stored in soils until subsequent precipitation events mobilize them into nearby water bodies. The study further showed that the export of agrochemicals to rivers is strongly controlled by rainfall intensity and amount, highlighting the importance of hydrological variability in determining contaminant transport during and after drought periods. Similarly, research on pesticide degradation processes has shown that drought conditions reduce microbial degradation efficiency and extend pesticide persistence in soils, particularly under dry or anaerobic conditions that limit biological activity (Dhakal et al., 2025). The persistence and mobility of pesticides during drought have important implications for water quality in agricultural watersheds. Pesticide stability has been noted to be closely linked to environmental conditions and compound half-life, with persistent pesticides posing longer-term risks to hydrological systems (Rad et al., 2022). Pesticides that are not readily degraded may accumulate in soils and later be transported into surface waters and groundwater systems through diffusion, dispersion, and infiltration (Syafudin et al., 2021). Reduced streamflow and lower water volumes during drought can therefore intensify pesticide concentrations through reduced dilution capacity, increasing potential risks to downstream ecosystems and water supplies.

The conversion of agricultural and natural lands to urbanized areas further compounds drought vulnerability. As documented by Azadi et al. (2018), land conversion to urban areas reduces groundwater volumes, lowers water reserves in aquifers, and increases the extent and frequency of intense floods. All of these factors increase exposure to drought and its impact on water quality. Impervious surfaces linked with urban development disrupt runoff patterns, decreasing infiltration and groundwater recharge during wet periods while boosting surface runoff during storm events. During drought, reduced baseflow from depleted groundwater is a direct consequence of reduced recharge, and the accumulated pollutants on impervious surfaces, including heavy metals, hydrocarbons, and

pathogens, are then delivered in concentrated pulses to water bodies during intermittent storm events.

The social and economic dimensions of drought and land-use interactions are also significant. Severe socioeconomic consequences of drought have been documented in agricultural regions, including dramatic losses in crop yield, rural employment, and agricultural income in drought-affected areas of India (Azadi et al., 2018). These economic pressures can lead to unsustainable land-use decisions, such as intensifying irrigation or converting wetlands to agricultural use, which further erode catchment hydrological resilience. Increase demand for water during drought may lead to high levels of water extraction that accelerate the damaging impacts of drought, a dynamic also called “the death by a thousand cuts” in reference to the cumulative effect of numerous small extractions that collectively accelerate drought impacts on aquatic systems (Bond et al., 2008). In this way, human responses to drought (driven by economic necessity) can themselves become drivers of hydrological stress, creating a feedback loop in which socioeconomic vulnerability and water scarcity mutually reinforce one another. Groundwater over-extraction to compensate for reduced surface water availability depletes aquifer reserves that would otherwise buffer drought impacts, while the expansion of irrigated agriculture increases consumptive water use precisely when water availability is most limited. Similarly, the removal of riparian vegetation and wetlands to expand agricultural production reduces the natural water retention capacity of catchments, amplifying runoff variability and reducing baseflow during dry periods. These human-induced modifications to the hydrological cycle compound the climatic drivers of drought, making it increasingly difficult to attribute water stress to natural variability alone.

The relationship between human water demand and drought forms a feedback loop, in which the effects of drought are intensified by the actions people take to cope with it. This condition has been described as anthropogenic drought, an imbalance between water supply and demand, largely driven by human changes to the hydrologic cycle, that causes water shortages to persist even during wetter periods (AghaKouchak et al., 2021). In this context, land use and human activities are not just influencing drought impacts but actively contributing to ongoing water scarcity. Consequently, distinguishing between natural drought and human-induced water stress becomes more challenging. This change significantly affects how drought is defined, tracked, and managed, highlighting the importance of integrated strategies that account for both climate variability and human impacts in tackling water quality issues.

7. Adaptive Responses for Managing Drought Impacts on Water Quality and Quantity

The evidence reviewed across hydrological, physical, chemical, and biological dimensions underscores that reactive, crisis-driven responses to drought are insufficient. Beyond affecting agricultural production and economic development,

drought can alter the behavior, transport, transformation, and accumulation of pollutants within river basins, ultimately affecting water quality and posing additional risks to water security (Bi et al., 2023). The scientific and managerial response to drought has historically been uncoordinated, reflecting a broader failure to anticipate and prepare for drought impacts before they escalate (Bond et al., 2008). This is compounded by the fact that drought is difficult to define in real time, normally its only recognized after it has already been occurring for some time (Humphries & Baldwin, 2003), making early, proactive governance frameworks essential. This urgency is reinforced by arguments that current water management practices require fundamental re-evaluation to align with the evolving realities of climatic extremes and ensure long-term resilience and sustainability (Park et al., 2026).

At the water supply level, groundwater management deserved particular attention. During drought, fast discharge pathways such as surface runoff and interflow diminish, leaving streamflow increasingly dependent on slower groundwater contribution (Hellwig et al., 2022; Van Loon, 2015). Groundwater storage can buffer hydroclimatic variability and maintain streamflow during dry periods, but this buffering capacity is compromised when anthropogenic withdrawals accelerate depletion (Hellwig et al., 2022; Vega-Briones et al., 2024). Adaptive options here include managed aquifer recharge, coordinated use of surface water and groundwater reserve, and regulated extraction limits during drought periods. Drought-driven changes in lake and reservoir hydrodynamics have further been shown to have profound consequences for drinking water supply, increasing both the technical difficulty and cost of treatment, which underscores the need to integrate water quality thresholds, not just quantity metrics, into drought management frameworks (Sun et al., 2025).

In managed ecosystems, such as agroecosystems and managed forests, drought impacts are shaped not only by climatic conditions but also by management strategies and land-use practices (Van Loon et al., 2024). These systems therefore provide important opportunities for targeted adaptation, particularly through changes in water use, agricultural practices, and land management. Agricultural water use represents one of the highest-leverage areas for adaptation. Farmers are also among the primary users of climate services for drought management, reflecting their direct exposure to drought impacts and the importance of agricultural production to food security (Muller et al., 2024). Agriculture and water-saving irrigation practices have been explicitly recommended to be adapted for future drought conditions, including the adoption of less water-consuming crops where feasible (Afzal & Ragab, 2019; Wang et al., 2025b). This is especially relevant given that salinity increases under drought are largest in irrigated regions (Graham et al., 2024), and that anthropogenic groundwater withdrawals for irrigation can worsen both drought deficit and duration (Vega-Briones et al., 2024). At the catchment scale, blue-green infrastructure and improved fertilization management have been pointed to as tools for reducing nutrient loads reaching water

bodies, noting that each reservoir responds differently to catchment-level land use and pollution pressures (Becher et al., 2024). Because the lack of regular flushing during drought allows solutes to accumulate in catchments (Clark et al., 2017), nutrient and contaminant management strategies need to account for the post-drought pulse, not just in-drought conditions.

The role of human activity in amplifying drought impacts means that technical solutions alone are insufficient. In many regions, a large imbalance between water supply and demand, driven by decades of anthropogenic alteration of the hydrologic cycle, has been shown to cause water shortage to persist even during wet years (AghaKouchak et al., 2021). Increased water extraction during drought, from large-scale irrigation to numerous small domestic and stock withdrawals, has similarly been documented to hasten damaging impacts and delay ecological recovery (Bond et al., 2008). Addressing these dynamics requires institutional commitment alongside technical intervention. Effective drought mitigation requires wise management and cooperation across communities and societies (Haile et al., 2020), including those sharing transboundary river basins, and that protecting livelihoods from drought shocks must be a core governance principle. Effective drought mitigation has been argued to require wise management and cooperation across communities and societies, including those sharing transboundary river basins, with protecting livelihoods from drought shocks framed as a core governance principle (Haile et al., 2020).

Finally, monitoring frameworks must extend beyond drought duration to capture the full impact arc, including the recovery phase (Clark et al., 2017). Elevated nutrient and contaminant concentrations have been confirmed to occur both during and after extreme droughts, as reduced catchment runoff increases the relative contribution of point source pollution (Sun et al., 2025). Integrating drought indices such as the SPI, SPEI, and PDSI, shown to quantify drought severity and duration under future climate scenarios (Nam et al., 2015), with real-time water quality monitoring would enable earlier detection of threshold crossings and more targeted management responses. Future research should also evaluate drought-contaminant interactions across a broader range of water-scarcity conditions and contaminant concentrations, particularly for pesticides whose exposure can become intermittent as hydrological conditions change (Arenas-Sánchez et al., 2016). As noted by Yang et al. (2026), continued global warming and population growth will place excessive pressure on water resources and increase the frequency of drought events, making the transition from reactive crisis management to anticipatory, systems-level adaptation not merely a scientific goal but an operational necessity.

8. Conclusion

Water is the ultimate resource for life, yet most terrestrial ecosystems experience episodic drought, during which limited moisture constrains microbial activity, organic matter decomposition, and nutrient mineralization (Schimel, 2018).

Drought is therefore one of the most pressing threats to hydrologic and freshwater systems worldwide, with consequences extending far beyond simple water scarcity. This review delved into some of the scope of drought impacts across physical, chemical, and biological dimensions, revealing an interconnected web of degradation that reshapes ecosystems at every level. Drought events globally are increasing in frequency, severity, and duration. Rising temperatures drive greater evapotranspiration, while precipitation patterns become more variable and unpredictable. These changes create conditions where drought can intensify even in regions receiving increased total rainfall, fundamentally challenging traditional assumptions about water security. The hydrological responses to drought establish the foundation for all subsequent impacts. Surface water availability declines rapidly during dry periods, while groundwater systems face sustained depletion that can persist for months or years after the meteorological drought ends. The loss of hydrological connectivity fragments hydrologic systems, isolating pools and disrupting the movement of water, nutrients, and organisms through landscapes. These changes reshape the physical environment, exacerbating water quality degradation.

Physical alterations during drought include elevated water temperatures, disrupted sediment dynamics, modified turbidity patterns, and increased concentrations of dissolved materials. These changes do not occur in isolation but rather create conditions that drive further chemical and biological transformations. Water temperatures rise as thermal capacity declines, dissolved oxygen concentrations drop, and salinity increases as evapotranspiration concentrates remaining water. These physical stressors establish an environment increasingly hostile to aquatic life and increasingly challenging for human water use.

Chemical water quality deteriorates through multiple pathways during drought. Nutrient dynamics become disrupted as reduced dilution capacity concentrates pollutants, while point sources become proportionally more significant. Nitrogen and phosphorus cycling undergoes fundamental alterations, with accumulated nutrients in soils and sediments creating the potential for severe water quality impacts during post-drought flushing events. Dissolved oxygen declines through elevated temperatures, increased stratification, and enhanced decomposition of accumulated organic matter. Heavy metal concentrations increase substantially through both concentration effects and altered redox conditions that mobilize metals from sediments. pH can shift to extreme values through processes such as pyrite oxidation in exposed sediments. These chemical changes persist well beyond the drought period itself, with accumulated contaminants released during rewetting events.

Biological communities respond to drought by altering conditions across all trophic levels. Harmful algal blooms are becoming more frequent in lakes and reservoirs as elevated temperatures, stronger stratification, and increased nutrient concentrations create ideal conditions for growth. Invertebrate communities lose sensitive species and exhibit slow recovery, particularly in systems already stressed

by poor water quality and altered flows. Fish populations face habitat fragmentation, thermal stress, and reduced connectivity to critical refugia. The loss of habitat diversity and ecological complexity during drought can push ecosystems toward simplified states dominated by disturbance-tolerant species.

Throughout this review, human activities and land use changes emerge as critical factors that intensify drought impacts. Agricultural water withdrawals accelerate the depletion of already stressed water sources. Nutrient management practices interact with drought to produce downstream water quality degradation. Urban development reduces groundwater recharge and concentrates pollutants. The concept of anthropogenic drought highlights that water scarcity increasingly reflects human demand and management decisions as much as climatic variability. In many regions, it has become difficult to separate natural drought from human-induced water stress.

Several significant knowledge gaps remain. The mechanisms and timescales of ecosystem recovery after drought remain poorly understood, particularly whether severely impacted systems can return to their original states or instead transition to alternative ecological configurations. The role of refugia in maintaining biodiversity during drought requires more attention, especially as habitat connectivity continues to decline. How repeated drought events interact to affect ecosystems over time remains unclear, raising concerns about potential tipping points. The socioeconomic dimensions of drought and their feedback with ecological impacts need better integration into research and management frameworks. In addition, research documenting changes in water color and total dissolved solids (TDS) during drought conditions remains limited, despite their importance as indicators of changing water chemistry and pollutant concentration. Similarly, studies examining variations in total bacterial counts during drought remain scarce, limiting understanding of how prolonged low-flow conditions and reduced dilution capacity influence microbial water quality and potential public health risks.

Effective drought responses should shift from reactive crisis handling to comprehensive, long-term strategies. These strategies need to tackle both climate-related and human-driven factors of water scarcity. Water management must recognize that drought effects can last long after normal rainfall resumes, and recovery may be slow or incomplete. At the supply level, protecting groundwater buffering capacity through regulated extraction and coordinated use of surface water and groundwater reserves is essential, alongside reservoir operating rules that account for water quality deterioration, not just storage volume. Agricultural practices need to balance productivity with water conservation, including irrigation scheduling adjustments and nutrient management strategies that account for the post-drought contaminant pulse. Land-use planning should incorporate hydrological resilience alongside other goals, and monitoring frameworks must extend beyond the declared end of drought events to capture the full trajectory of chemical and biological recovery. Urban development should safeguard groundwater recharge and reduce pollutants.

Drought challenges all facets of freshwater management, threatening ecosystems and human water security. As climate change worsens drought conditions globally, the importance of ongoing research, flexible management, and institutional dedication grows. The evidence from this review shows drought is not just a temporary problem but a transformative force that can alter freshwater systems in ways that are hard or impossible to reverse. Addressing this issue involves understanding the complex impacts of drought across hydrological, chemical, biological, and social aspects, and creating integrated strategies that foster resilience in both natural and managed systems.

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Author Contributions

Conceptualization, S.A.B. and J.E.Q.; methodology, S.G.D.; formal analysis, S.G.D.; investigation, S.G.D.; writing—original draft preparation, S.G.D.; writing—review and editing, S.A.B., J.E.Q. and S.F.; visualization, S.G.D.; supervision, S.A.B., J.E.Q. and S.F.; funding acquisition, J.E.Q. and S.F. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations

The following abbreviations are used in this manuscript:

CMIP5	Coupled Model Intercomparison Project Phase 5
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SC-PDSI	Self-Calibrating Palmer Drought Severity Index
IPCC	Intergovernmental Panel on Climate Change
NIDIS	National Integrated Drought Information System
USDM	U.S. Drought Monitor
GRACE	Gravity Recovery and Climate Experiment
TSS	Total Suspended Solids
EC	Electrical Conductivity
SRP	Soluble Reactive Phosphorus
DOP	Dissolved Organic Phosphorus
PP	Particulate Phosphorus
TP	Total Phosphorus
DO	Dissolved oxygen
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
SWAT	Soil and Water Assessment Tool
TDS	Total Dissolved Solids