

Review

A Review on Climate Change Impacts on Freshwater Systems and Ecosystem Resilience

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Abstract

Climate change is fundamentally transforming global water systems, affecting the availability, quality, and ecological dynamics of water resources. This review synthesizes current scientific understanding of climate change impacts on hydrological systems, with a focus on freshwater ecosystems, and regional water availability. Rising global temperatures are disrupting thermal regimes in rivers, lakes, and ponds; intensifying the frequency and severity of extreme weather events; and altering precipitation and snowmelt patterns. These changes place mounting stress on aquatic ecosystems, threaten water security, and challenge conventional water management practices. The paper also identifies key vulnerabilities across diverse geographic regions and evaluates adaptation strategies such as integrated water resource management (IWRM), the water, energy and food (WEF) nexus, ecosystem-based approaches (EbA), the role of advanced technology and infrastructure enhancements. By adopting these strategies, stakeholders can strengthen the resilience of water systems and safeguard critical resources for both ecosystems and human well-being.

Keywords: climate change; water resources; ecosystems; adaptation strategies; hydrological impacts; resilience



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1. Introduction

Climate change is increasingly recognized as a dominant force driving profound shifts in the Earth's water systems. Wetlands, rivers, ponds and lakes are crucial components of freshwater ecosystems and are especially vulnerable. Water resources are fundamental to human life and are the backbone of socioeconomic development. They support critical sectors such as agriculture, industry, sanitation, and overall human health and well-being [1–3]. Beyond these uses, water resources are also essential for environmental sustainability, helping maintain biodiversity, carbon cycling and regulating climate patterns [4–6]. However, warming temperatures, intensified extreme weather events and altered hydrological cycles threaten to undermine these functions [7–9]. For example, in regions like the Upper Blue Nile Basin, water resources are essential for agriculture, hydropower generation, and

domestic use. Projections based on RCP4.5 and RCP8.5 scenarios indicate declining rainfall and rising temperatures, which may lead to reduced streamflow, lower surface runoff, and decreased overall water yield, particularly during the dry season. Simultaneously, increasing temperatures are expected to intensify evapotranspiration, further straining limited supplies. These projected changes carry serious implications for food production and water security, underscoring the need for adaptive water management strategies to mitigate such risks [10].

Climate-induced changes in water temperature affect lake stratification, nutrient rich runoff and oxygen availability, leading to more frequent algal blooms and habitat loss for cold-water species [8,11,12]. These blooms degrade water quality, threaten aquatic biodiversity, and pose health hazards [13]. Shifts in snowmelt timing and precipitation distribution alter river flow regimes, disrupting agricultural practices and water supply systems [14,15]. Wetlands, for instance, are particularly vulnerable to shifts in temperature and precipitation patterns. Under warming conditions, especially when coupled with drought, wetland respiration rates can surpass primary production, converting them from carbon sinks into carbon sources [7]. Lakes worldwide are also exhibiting significant thermal responses to climate change. A global study covering 235 lakes showed that lake surface water temperature (LSWT) increased by an average of 0.34 °C per decade between 1985 and 2009 [8]. Thermal stratification intensifies as surface waters warm more rapidly than deeper layers, limiting vertical mixing and oxygenation. Permafrost thaw and increased evaporation are causing shallow ponds to shrink or disappear entirely, disrupting local biodiversity and carbon storage [16]. As a result, the sustainable management of water resources has become more pressing than ever, requiring innovative approaches that balance the needs of society, the economy, and the environment [17].

Although a growing body of research has examined how climate change affects hydrological and ecological processes, several important gaps remain. Many studies still look at individual components of freshwater systems rivers, lakes, wetlands, or groundwater separately, rather than viewing them as interconnected parts of a larger whole. This narrow focus makes it difficult to understand how changes in one system influence others, or how these linked changes can inform practical adaptation and management strategies. Another limitation lies in the geographical focus of current research. Much of what is known comes from temperate and boreal regions, while tropical, arid, and high-altitude areas such as the Hindu Kush Himalaya and Sub-Saharan Africa remain understudied, despite being among the most climate-sensitive and water-dependent parts of the world.

A third gap exists at the interface between science and policy. While evidence of climate impacts on freshwater systems continues to grow, it is often not translated into governance frameworks or decision-making tools. Approaches such as Integrated Water Resources Management (IWRM) and the Water–Energy–Food–Ecosystem (WEFE) nexus are widely discussed, yet rarely informed by the latest hydrological and ecological insights. Similarly, emerging technologies like machine learning, remote sensing, and GIS offer powerful ways to detect change and support adaptive planning, but their policy relevance and integration remain limited.

In response to these challenges, this review aims to:

1. To synthesize recent (2010–2025) peer-reviewed research on climate-driven changes in freshwater systems including hydrological shifts, thermal dynamics, and ecosystem responses across rivers, lakes, wetlands, ponds, and groundwater in diverse climatic regions.
2. To identify and analyze critical knowledge, data, and methodological gaps that limit cross-system understanding and hinder the translation of climate-science evidence into actionable freshwater management and resilience planning.

3. To evaluate and integrate adaptation and governance strategies including nature-based solutions, Integrated Water Resources Management (IWRM), the Water–Energy–Food–Ecosystem (WEFE) nexus, and emerging technological tools (AI, GIS, and remote sensing) within a unified DPSIR (Drivers-Pressures-States-Impacts-Responses) framework to guide evidence-based, regionally adaptable water-management decisions.

Overall, the mounting evidence indicates that freshwater ecosystems are undergoing rapid and profound transformations under climate change. Therefore, adaptive, data-informed, and forward-looking water governance and management strategies are crucial to ensure the resilient and sustainable use of freshwater systems in a changing climate [17]. While this review is thematically structured around hydrological shifts, temperature impacts, and ecosystem responses, it extends beyond summarizing trends by identifying key research and management gaps at the intersection of climate science and water governance. By translating these insights into actionable themes, hydrological change, thermal dynamics, adaptation and governance, and emerging technologies, this review provides a framework to guide decision-making and future research priorities for sustainable water resource management in a changing climate. Guided by the DPSIR (Drivers-Pressures-States-Impacts-Responses) framework, the review connects climate-related drivers with changes in freshwater systems and the responses they trigger, offering a comprehensive perspective on water-system resilience. Building on this conceptual overview, the following section outlines the theme-guided methodology used in this review. The approach combines systematic literature screening with thematic synthesis across six domains: hydrological change, thermal impacts, coastal vulnerability, adaptation and governance, and emerging technologies, to ensure comprehensive and policy-relevant coverage of recent research.

2. Methodology

This review employs a systematic, theme-guided synthesis approach to compile and analyze recent peer-reviewed research on the effects of climate change on freshwater systems. Only peer-reviewed, English-language publications published between 2010 and 2025 are included in the evidence base. A consistent multi-database search strategy was adopted across all thematic sections, drawing primarily from Web of Science, Scopus, ScienceDirect, and Google Scholar to ensure comprehensive and unbiased literature coverage. Foundational background; hydrological change (precipitation, snowmelt, river flows); thermal regimes and ecosystem responses; water-resource adaptation and governance; and emerging technologies and modeling are the five domains that organize searches and reflect the structure of this paper. The targeted keyword sets were applied to the databases listed in Table 1 for each domain. These sets combined climate-change terms with phrases specific to the system and response (e.g., “precipitation extremes,” “snowmelt,” “river flows”; “water temperature,” “thermal stratification,” “algal blooms”; “IWRM,” “governance,” “adaptation”; “AI,” “machine learning,” “remote sensing,” “GIS”). Using platform-appropriate wording (truncation, phrase quotes, and fielded title/abstract queries when available), a targeted collection of peer-reviewed records from the 2010–2025 timeframe was used.

Two levels of screening were conducted to guarantee topical relevancy and fundamental methodological soundness. In order to eliminate off-topic or non-peer-reviewed content and to verify an explicit climate-freshwater linkage within the target domain, titles and abstracts were initially examined. Before being included, whole texts were evaluated to confirm their substantive contribution and thematic fit. The primary response metrics (e.g., precipitation or flow timing, lake-surface temperature and stratification, dissolved oxygen or harmful algal blooms), the focal climate driver or stressor, the geographic setting and system type (river, lake, reservoir, wetland, groundwater), and any adaptation or governance approaches reported (e.g., IWRM, nature-based solutions, managed aquifer

recharge, green/grey infrastructure) were all taken into consideration during the data extraction process. Per-section counts may overlap since individual research might inform many domains; the synthesis is based on a distinct corpus of literature that includes about 163 studies. According to journal practice, figures and quantitative values obtained from cited literature are given credit to their original sources. To ensure that the synthesized evidence is directly usable for water managers and policymakers, each thematic domain was also evaluated for its policy relevance. During data extraction and synthesis, studies were mapped to decision-making contexts such as reservoir operation, flood and drought design standards, and water-quality objectives. This screening step ensured that the five analytical domains not only summarized scientific progress but also linked results to actionable adaptation and governance instruments. While the review adopts a structured narrative approach, it does not follow a strict systematic review protocol but strives to ensure a broad and balanced representation of current research. Section counts may overlap across themes while total unique studies considered were approximately 153 as shown in Table 1.

Table 1. Summary of review structure, literature coverage, and data sources (2010–2025; peer-reviewed).

Section	Number of Papers	Main Keywords	Data Sources/Databases	Notes
Introduction and Background	25	Climate change; freshwater ecosystems; vulnerability	Web of Science; Scopus; ScienceDirect; Google Scholar	Foundational concepts and context
Hydrological Changes (Precipitation)	50	Precipitation extremes; snowmelt; river flows	Web of Science; Scopus; ScienceDirect; Google Scholar	Changing hydrological regimes
Thermal Regimes and Ecosystems	40	Water temperature; stratification; fish; algal blooms	Web of Science; Scopus; ScienceDirect; Google Scholar	Impacts on aquatic life and thermal processes
Water Resource Adaptation Strategies	25	IWRM; policy; governance; adaptation	Web of Science; Scopus; ScienceDirect; Google Scholar	Managing water under climate stress
Emerging Technologies and Modeling	13	AI; machine learning; remote sensing; GIS	Web of Science; Scopus; ScienceDirect; Google Scholar	Monitoring and prediction tools
Total (approx.)	≈153			Unique studies underlying the synthesis

3. Climate Change Impacts on Freshwater Systems and Strategies for Adaptation

3.1. Climate Change and Hydrological Shift

Climate change is fundamentally reshaping the global hydrological cycle, leading to changes in the amount, intensity, timing, and type of precipitation. These changes, in turn, affect snow accumulation and melt, streamflow patterns, and groundwater recharge. Understanding how these processes are shifting is critical to managing water resources sustainably under a changing climate.

3.1.1. Impact of Climate Change on Precipitation Patterns, Snowmelt Timing, and River Flow Dynamics

One of the most widely used datasets for assessing climate-induced changes in precipitation extremes is the HadEX2 dataset, a global gridded archive of climate indices based on daily weather station observations. This dataset reveals a significant rise in the

frequency and intensity of extreme precipitation events over the past century, particularly in regions such as eastern North America, Asia, and South America. An increase in heavy precipitation days (R10mm) and the proportion of rainfall from very wet days (R95pTOT) suggests disruptions to snowmelt timing and river flow regimes [14].

Contractor et al. also emphasize that climate change has intensified daily precipitation patterns worldwide. The increase in rainfall intensity across all categories, from light to heavy rainfall, particularly in areas like Europe, Australia, and North America, is notable. These changes are expected to affect snowmelt, with more precipitation falling as rain in colder regions, leading to earlier snowmelt and shifts in river flows. The study also highlights that more frequent and intense precipitation events can exacerbate river flooding, further influencing river flow patterns [18]. The impacts of climate change on freshwater resources are pronounced in highland regions and arid zones. In Eastern Africa, shifting rainfall patterns and rising temperatures have intensified both floods and droughts, severely affecting streamflow and aquifer recharge. For instance, projections suggest an 81% increase in streamflow by 2080 in Ethiopia's Geba River [19] and a 74% decrease in Lake Ziway's outflow under future climate scenarios [20]. Meanwhile, the Tibetan Plateau and Xinjiang have witnessed an expansion of surface water bodies, primarily due to glacial melt and permafrost degradation [21,22]. Markonis et al. reinforce these findings by reporting an overall increase in total precipitation and wet days globally, with a notable rise in heavy precipitation events. In regions dependent on snowmelt for water, these changes may lead to earlier and more intense river flows, disrupting traditional water availability cycles [15]. Schneider et al. demonstrate that rising temperatures and altered precipitation patterns significantly shift both the timing and magnitude of river flows particularly by reducing snowmelt-driven flows in boreal regions and decreasing overall runoff in Mediterranean areas [23].

In Bangladesh, significant changes in rainfall patterns have been observed, particularly in Sylhet, with overall annual rainfall increasing while monsoon rainfall declines. This variability in precipitation timing could alter river flow patterns, impacting agricultural productivity and water management. The shift in rainfall from the monsoon season to the pre-monsoon months could further affect water availability and flood risks [24]. Similarly, research on China's river basins indicates that climate change will intensify precipitation extremes, especially in high-elevation and high-latitude areas. This will lead to earlier snowmelt, affecting river flow seasonality and increasing flood risks in these regions [25]. Increased rainfall intensity during the East Asian Summer Monsoon in southeastern China has also been linked to higher flood risks, potentially altering river flow patterns in the Yangtze River basin [26].

Asian regions reliant on winter snow accumulation are now receiving more winter rainfall, disrupting snowpack formation and leading to earlier runoff, thereby challenging traditional water availability timelines [27]. However, Sharma et al. caution that more intense rainfall does not always translate into more flooding, citing variables like decreased snowmelt, lower soil moisture, and smaller storm footprints [28]. Likewise, Wasko and Sharma (2017) show that while rainfall extremes are increasing, evapotranspiration is also rising with temperature, offsetting streamflow increases in many areas though small catchments still face higher flood risks during intense events [29].

Donat et al. highlight a global surge in daily precipitation extremes, which elevates flood potential even if total precipitation trends remain uncertain [30]. In Turkey, a 1 °C temperature increase corresponds with a 6% decrease in total rainfall and a 3% rise in prolonged dry spells, stressing streamflow regimes [31]. More broadly, each 1 °C warming leads to a 7% increase in atmospheric moisture capacity, intensifying rainfall and runoff in spring while boosting drought risks in summer [32].

In the Alpine region, high-resolution modeling suggests that a 4 °C temperature rise by century's end could advance snowmelt-driven runoff by up to three months—challenging current reservoir operations and seasonal water planning [33]. In the Mississippi River Basin, dramatic increases in extreme humid nights and days suggest shifts in hydrological processes through enhanced evaporation and altered precipitation cycles, although stream-flow trends remain ambiguous due to complex land-use and soil dynamics [34,35]. While observed precipitation extremes have improved water supply reliability in some cases, climate models still project declining water reliability overall, underscoring the uncertainties in future river flow predictions [36]. Figure 1 illustrates how warmer climates alter the timing and type of precipitation, leading to earlier snowmelt and increased flood risk. In contrast, cooler climates support delayed snowmelt and more stable river flow conditions.

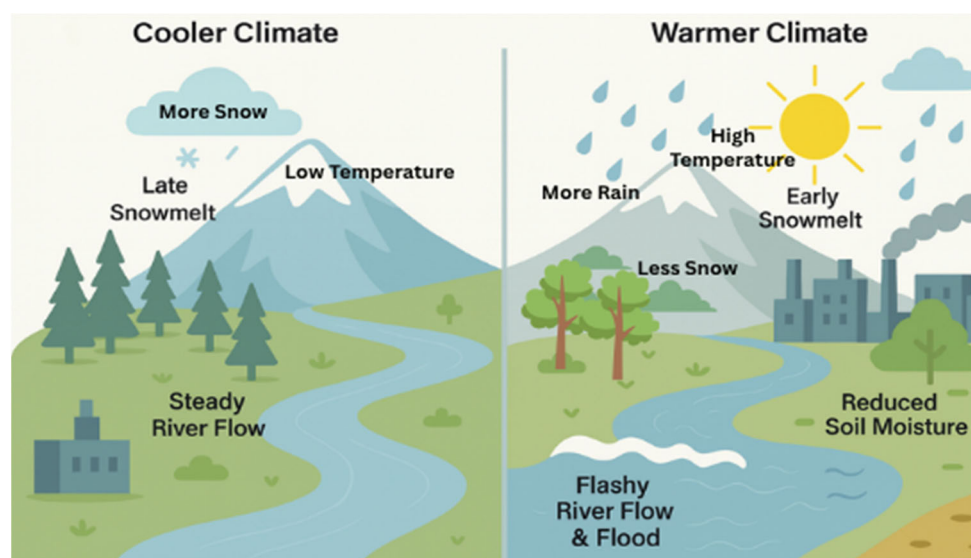


Figure 1. Schematic illustration showing the effect of warming on snow accumulation, earlier snowmelt, and its consequences for river flow and flood dynamics. (Conceptual illustration initially AI-generated using OpenAI DALL·E 3 and manually refined in Canva).

3.1.2. Effects of Hydrological Changes on Water Availability, Quality, and Ecosystem Functioning

Shifting precipitation patterns and altered snowmelt cycles are collectively challenging water management systems across the globe. In the northwestern United States, for example, projections indicate a reduction in summer precipitation coupled with increased rainfall in fall and winter. This seasonal shift alters snowpack and streamflow timing, reduces summer water availability, and elevates water temperatures, affecting agriculture, hydropower, and aquatic ecosystems [37]. As the hydrological cycle intensifies, Tabari notes that although humid regions might see more precipitation, flood risks rise, and so does pollution from runoff. In contrast, arid and semi-arid regions may not benefit, as higher evaporation can offset any rainfall increases, reducing effective water availability [38]. Donat et al. and Tabari further caution that extreme rainfall events can cause flash floods, which degrade water quality by transporting sediment, nutrients, and pollutants into rivers and lakes [30,39]. In cold regions like Siberia, increased precipitation is destabilizing permafrost, changing groundwater flows, and posing new flooding and contamination risks to ecosystems already sensitive to warming [40]. Similar concerns arise in Pamplona and India's river basins, where intensified rainfall is heightening flood risks, compromising infrastructure, and accelerating water quality degradation through increased runoff [41,42].

The Hindu Kush Himalayan (HKH) region encompasses more than 54,000 glaciers and a drainage basin of 2.8 million km², making it one of the most critical freshwater

reserves globally. Rising temperatures and altered precipitation patterns are accelerating glacier mass loss, modifying runoff regimes, and degrading water quality, with cascading consequences for ecosystems and downstream populations [43]. However, there has been more rapid alteration on the properties of water resource due to change in climatic variables, impacting overall ecosystem. A shift in precipitation patterns has directly contributed to the expansion of lake areas in the Hindu Kush-Himalaya-Tibetan (HKHT) region, along with increased runoff in major tributaries such as the Indus and the Ganges, by 12.8–29.0% and 3.3–6.1%, respectively. These changes are expected to ultimately intensify water-related hazards in South Asia [44]. A study from Nepal reported that the temperature in Hindu Kush region has been increased in a rate of 0.28 °C/decade and even the extreme precipitation is projected to increase by 4–12% resulting glacial mass melting, GLOF and flash flooding [45]. Consequently, Nepalese glaciers are facing heterogeneous shrinkage, negative mass balance and reduction in ice volume [46]. From 1910 to 2015, in the Kokcha sub-basin of the Afghanistan Range, studies estimated the reduction of ~84 km² (~15%) of the total glaciated area [47]. Similarly, in Pakistan, out of 162 identified glacial lakes, 31 have been classified as potentially dangerous, exacerbating the risk of GLOFs for downstream communities [48]. Beyond the projected risks, past flood events in the region provide critical evidence of how such hazards translate into ecological consequences. Recently, in 2024, GLOFs in Thame Valley, Solukhumbu, caused major agricultural losses, water contamination, and damage to trails, landscapes, and local biodiversity [49]. The sudden outburst of a supraglacial lake on the Purepu Glacier triggered a massive flood downstream in Nepal, altering river ecosystems, damaging riparian habitats, and affecting local communities by destroying the Miteri (Nepal–China Friendship) Bridge at Rasuwagadhi and disrupting trade and infrastructure [50,51]. Additionally, heavy rainfall from intense monsoon systems triggered catastrophic flash floods and mudflows, causing fatalities and widespread destruction, accompanied by landslides and severe soil erosion [52,53]. Alexander et al. and Westra et al. emphasize that extreme precipitation, now more frequent across many regions is overburdening water systems. Short-lived floods may replenish surface water but simultaneously introduce pollutants, stressing ecosystems and complicating water management [54,55]. The increased atmospheric moisture from warming, approximately 7% per 1 °C, further amplifies rainfall variability, increasing the likelihood of both floods and droughts, with cascading effects on water systems and ecosystems [56].

These complex interactions between climate-induced hydrological shifts and ecosystem health are summarized in Figure 2.

In mid- to high-latitude areas, frequent flood events are altering species habitats and straining aquatic biodiversity [57]. In Southeast Asia and eastern Africa, the interplay of heavy rainfall and prolonged dry spells is putting additional stress on already fragile ecosystems, threatening both biodiversity and ecosystem services [32]. For example, in the Mississippi River Basin, increases in extreme humid days and nights have led to heightened evaporation, reducing streamflow and threatening aquatic life [34].

In arid regions like the Eastern Mediterranean and Middle East, rising temperatures by as much as 0.45 °C per decade are intensifying droughts and flooding, degrading water quality, and accelerating desertification [58]. Globally, the frequency of extreme precipitation events is nearly doubling with each 1 °C of warming, creating a dual threat of more severe floods and longer droughts, both of which jeopardize water availability and ecosystem stability [59,60]. Especially in Southeast Asia and eastern Africa, projected increases in flood frequency are expected to significantly disrupt aquatic ecosystems and resource availability [61–63].

Collectively, these studies point to a troubling trend: while some regions may temporarily benefit from increased rainfall, the broader outcome is one of disruption, more

variability, degraded water quality, and increased ecosystem vulnerability. These changes underscore the urgent need for adaptive and integrated water resource management strategies that can withstand and respond to a more unpredictable hydrological future.

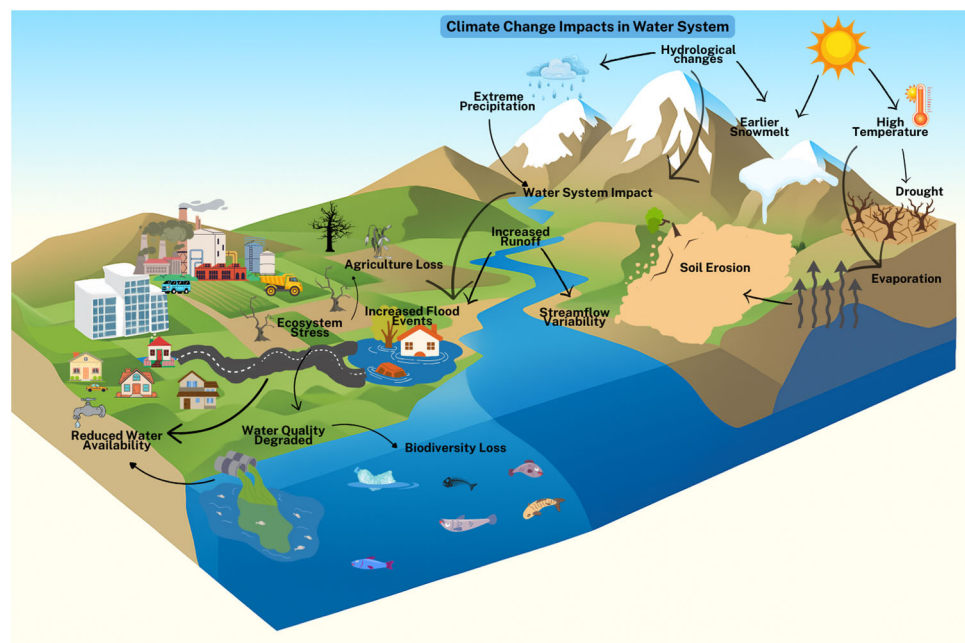


Figure 2. Schematic illustration showing cascading impacts of climate-driven hydrological changes on water availability, quality, and ecosystem functioning. (Conceptual illustration initially AI-generated using OpenAI DALL·E 3 and manually refined in Canva).

3.2. Rising Temperatures and Water Temperature

Rising global temperatures have far-reaching consequences on water bodies across the planet. Warming affects not only the surface temperature of rivers, lakes, and ponds but also the fundamental processes that support aquatic life. As freshwater systems respond to climate forcing, the ecological balance of aquatic ecosystems is shifting, posing risks to biodiversity, food security, and water resource sustainability.

3.2.1. Impact of Rising Temperatures on Water Temperature Regimes in Rivers, Lakes Ponds

Global warming is influencing the thermal structure of water bodies around the world, including rivers, lakes, and oceans, with significant implications for aquatic life. Water surface temperatures are expected to rise in response to projected global temperature increases of approximately 2.5 °C by the end of the century. Additionally, the increase in harmful algal blooms, spurred by warmer water, signals the urgency for mitigation and adaptation strategies [64–66].

In many lakes, prolonged thermal stratification and reduced overturning are already being observed, contributing to lower oxygen levels, shifts in species dominance, and greater methane emissions. For instance, in Lake Baikal, the upper 45–100 m of the water column has experienced considerable heat accumulation over two decades, while deeper layers show a cooling trend, reflecting disrupted thermal circulation. Lakes in Europe have also shown consistent warming. From 1966 to 2015, maximum annual LSWT in Eastern Europe rose by 0.58 °C per decade [11], narrowing cold-water species habitats and increasing the risk of hypoxia during summer months. In North America, the Great Lakes have shown seasonally altered stratification patterns due to air temperature increases. For example, Lake Michigan is experiencing earlier spring mixing and later fall turnover, modifying nutrient and oxygen dynamics [67]. Similarly, Chinese reservoirs are projected

to experience surface warming of up to 2.35 °C by 2100, increasing risks of eutrophication and algal bloom [68]. Arctic and subarctic lakes are also changing rapidly. In Finland's Lake Inari, rising air and water temperatures have led to earlier ice-off dates and longer open-water periods since the 1980s [69]. In Canada's Saint John River, projections suggest a 1 °C rise in water temperature between 2070 and 2074, with an additional 1 °C by 2100. This may reduce cold-water species habitats, such as those for Atlantic Salmon, while favoring warm-water species like Striped Bass [70]. Similarly, reversing trends in Arctic cooling, where the warmest decades were between 1950 and 2000 indicate significant ongoing changes in aquatic thermal regimes [71].

In the Pacific Northwest, rivers are projected to warm by 1 °C to 5 °C due to air temperature increases. These thermal changes will likely reduce streamflow and inundate low-elevation spawning grounds, disrupting species such as salmonids [72]. Permafrost degradation and higher evaporation rates in the Arctic are also causing millennia-old ponds to dry up, further threatening aquatic biodiversity [73]. Moreover, warming temperatures are exacerbating extreme weather patterns, particularly in tropical regions, resulting in more unpredictable water temperature fluctuations across aquatic systems [57]. The ecological consequences are severe. Increasingly frequent lake heatwaves and oxygen-depleted conditions contribute to fish die-offs, with one study projecting a 6- to 34-fold increase in such events by 2100 [74]. In Erhai Lake, China, rising air temperatures and declining wind speeds have increased evaporation, raising concerns about long-term water availability [75]. Tropical lakes face several challenges, with thermal zone overlap between historical and current periods falling below 81% in several systems, leaving endemic species highly vulnerable. Many species exhibit limited thermal plasticity, further compounding extinction risks under rapid warming. The cascading effects of warming across freshwater systems from reduced streamflow in rivers to oxygen depletion in lakes and the drying of Arctic ponds are conceptually summarized in Figure 3.

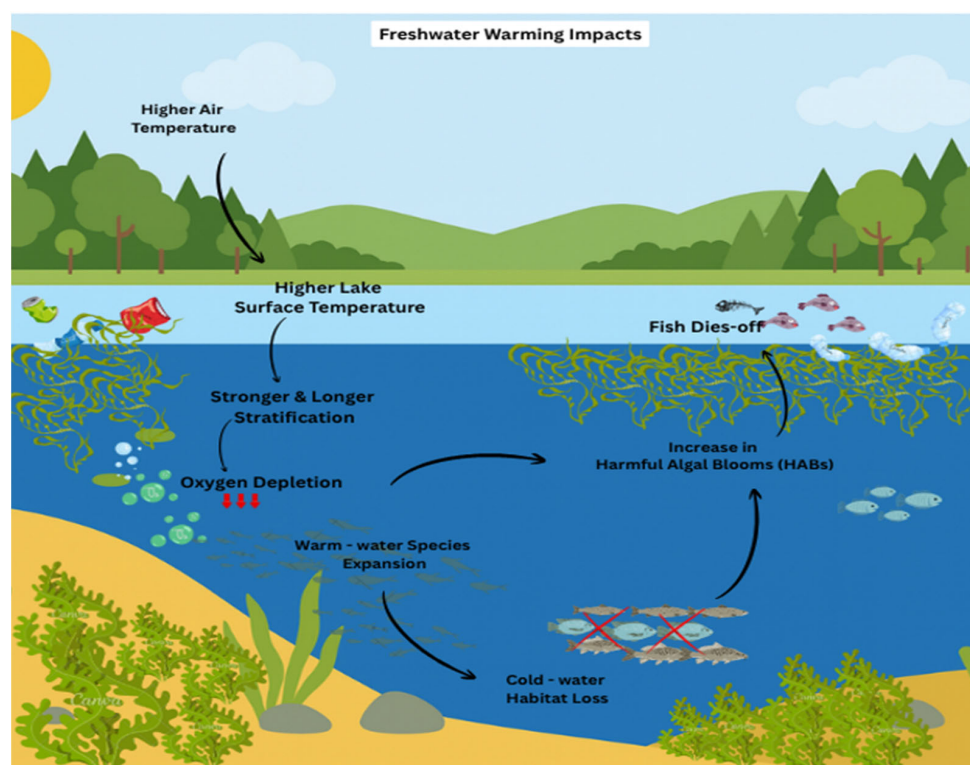


Figure 3. Schematic illustration showing the impact of rising temperatures on freshwater systems, leading to stronger stratification, oxygen depletion, harmful algal blooms, and habitat loss. (Conceptual illustration initially AI-generated using OpenAI DALL·E 3 and manually refined in Canva).

3.2.2. Impact on Aquatic Ecosystems, Species Distribution, and Thermal Stratification Processes

The effects of rising temperatures are already evident in species distribution and thermal stratification. Cold-water species, like salmonids, are losing habitat and moving to higher altitudes or latitudes [76]. Estimates show a reduction of 11–22% in suitable habitats for species like bull trout. On the other hand, warm-water species are expanding into new areas as temperatures rise. Additionally, the longer thermal stratification periods expected in lakes could lead to low-oxygen conditions in deeper waters, putting further stress on cold-water species [77]. Species like amphibians are particularly vulnerable, with about one-third at risk of extinction, reflecting broader declines in freshwater vertebrates [77].

Freshwater ecosystems are among the most threatened by rising temperatures, with biodiversity losses outpacing those in terrestrial environments [78]. In the northwestern U.S., unregulated rivers and streams showed warming trends from 1980 to 2009, with summer temperatures rising by 0.22 °C per decade. This has resulted in habitat loss for cold-water species like salmon, further stressed by declining summer stream flows [79]. Similarly, climate models predict that the Midwest will lose nearly 50% of its cold and cool-water fish habitats due to rising temperatures, disrupting species distribution and thermal stratification processes [80]. Climate change is causing cold-water species to decline and warm-water species to expand their ranges, reshaping freshwater ecosystems and altering thermal stratification processes [81]. U.S. streams and rivers have also seen long-term warming trends of 0.009–0.077 °C per year, especially in urbanizing areas. This warming could lead to eutrophication and disrupt ecosystem processes, further threatening aquatic biodiversity [82].

Rising temperatures are causing significant disruptions to water temperature regimes, leading to habitat loss for cold-water species, an increase in warm-water species, and changes in thermal stratification. Rising temperatures are causing significant disruptions to water temperature regimes, leading to habitat loss for cold-water species, an increase in warm-water species, and changes in thermal stratification. The findings in Figure 4 show that these shifts are already affecting aquatic ecosystems worldwide, emphasizing the need for adaptive management strategies to mitigate these impacts.

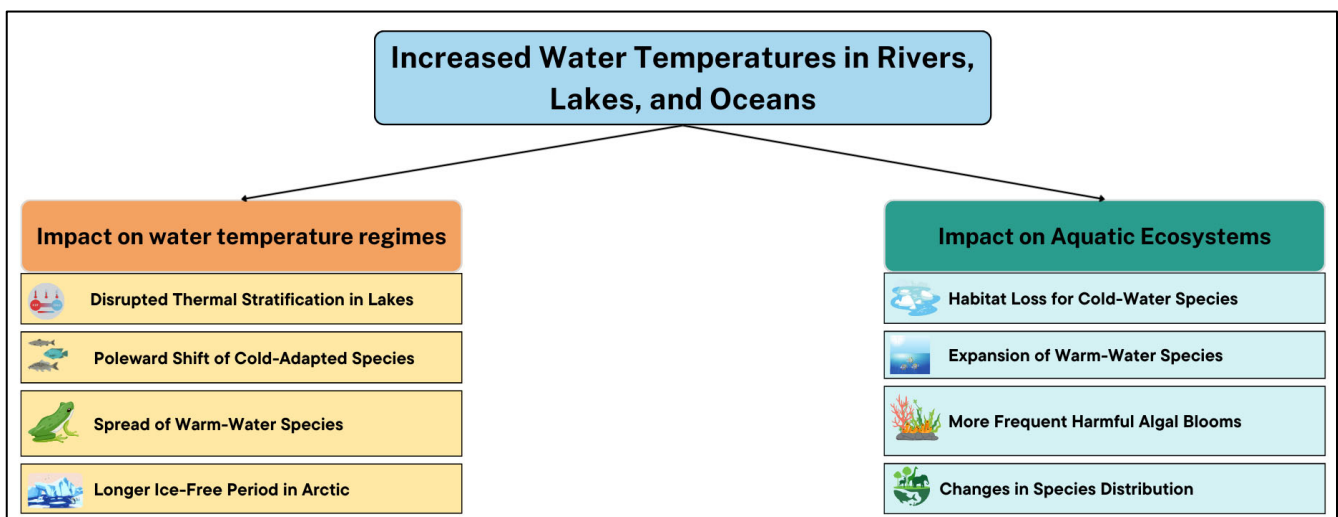


Figure 4. Conceptual flowchart summarizing the cascading effects of rising water temperatures on stratification processes, oxygen dynamics, aquatic species habitats, and ecosystem functioning. (Conceptual illustration initially AI-generated using OpenAI DALL·E 3 and manually refined in Canva).

3.3. Vulnerable Freshwater Systems: Shallow Lakes and Ponds

3.3.1. Shallow Lakes: Vulnerability to Warming, Stratification, and Nutrient Stress

Shallow lakes are among the most climate-sensitive freshwater systems due to their limited depth, large surface-to-volume ratio, and strong coupling with catchment processes. Shifts in rainfall and runoff directly alter nutrient and dissolved organic carbon (DOC) inputs, as well as water balance [83]. Rainfall extremes can drive contrasting outcomes: in Lake George, high rainfall increased dissolved color and mixing, suppressing blooms, whereas dry periods with low turnover favored dense cyanobacterial blooms [84]. Similarly, heavy rainfall may temporarily alleviate eutrophication by disrupting stratification, oxygenating bottom waters, and reducing algal biomass, though these effects fade once stratification re-establishes [85].

Temperature rise further amplifies pressures. In Lake Mangueira, Brazil, simulations suggested warming could increase transparency under meso-oligotrophic conditions due to continuous macrophyte growth [86]. More commonly, however, warming lowers nutrient thresholds for eutrophication by accelerating phosphorus release and favoring cyanobacteria, leading to higher chlorophyll-a, stronger algal dominance, and weakened zooplankton grazing. Combined with greater densities of zooplanktivorous fish, this destabilizes trophic interactions and reinforces turbid states [87]. Oxygen declines add further stress, driven by reduced atmospheric exchange and stronger stratification that limit bottom-water aeration [88].

Empirical evidence shows these processes in action. In Lake Champs-sur-Marne, water warmed by 0.6 °C per decade since 1960, double the air warming rate, intensifying stratification and extending cyanobacterial growth conditions, with harmful blooms more likely as nutrients were resupplied from sediments [89]. Loch Leven, Great Britain's largest shallow lake, contrasts by showing declining chlorophyll-a (96 µg L⁻¹ in 1969 to 27 µg L⁻¹ in 2001) following nutrient management that reduced soluble reactive phosphorus (SRP), though summer dominance by nitrogen-fixing cyanobacteria (*Anabaena* spp.) persists [90]. Across broader scales, climate change has partly confirmed predictions of higher richness at warmer locations, with fishes and phytoplankton benefiting while zooplankton and macroinvertebrates decline, resulting in smaller body sizes, weaker grazing pressure, stronger fish predation, and destabilized food webs [85].

Experimental work further illustrates these dynamics. In the Euro-limpac mesocosm study, shallow lakes heated by 4 °C reached 25 °C in summer compared to 21 °C in controls, never falling below 3 °C in winter. Warming increased soluble phosphate release, reduced fish biomass through oxygen stress, and, together with nutrient loading, intensified eutrophication and biodiversity loss [91].

3.3.2. Ponds: Disappearance from Permafrost Thaw and Evaporation Loss

Ponds are among the smallest and most vulnerable freshwater ecosystems, with their limited depth, small volume, and reliance on direct precipitation making them highly sensitive to global warming [92]. Even minor shifts in rainfall timing or intensity can disrupt their hydrological balance, while higher evaporation and more frequent droughts accelerate drying. Conversely, intense rainfall increases surface runoff at the expense of groundwater recharge, leaving ponds more unstable. These shifts also heighten sediment and contaminant inflows, reducing biodiversity, while elevated temperatures may further reshape communities by enabling non-native species to expand functional roles alongside natives [93].

Ecological stress is already evident worldwide. In the Czech Republic, warmer summers have lengthened periods of stressful water temperatures, threatening carp aquaculture under unprecedented regimes [94]. In India's semiarid regions, projections suggest pond

water temperatures will rise by up to 3.7 °C by 2080, increasing evaporation by nearly 30%, shortening hydroperiods by up to 26 days, and lowering oxygen concentrations by 2–6%, with severe consequences for persistence and ecosystem health [95]. Temporary ponds in hot regions may even reach lethal thresholds of 40–45 °C, where invertebrates such as fairy shrimp show altered oxygen metabolism to cope with extreme stress [96].

Altered environmental conditions also intensify disease risks. Warming, drying, and nutrient enrichment have been shown to increase parasite transmission, with higher infection rates in snails and greater amphibian deformities linked to *Ribeiroia* in nutrient-rich settings [97]. Such biological disruptions highlight that ponds face not only physical disappearance but also ecological destabilization.

In permafrost landscapes, losses are striking. Analysis of more than 2800 ponds across Arctic drained thaw lake basins revealed a 30% decline in area and 17% decline in number over six decades, driven by rising air temperatures, permafrost degradation, longer summers, and vegetation encroachment [98]. In Arctic and Subarctic regions, shorter ice-cover duration, warmer water, and stronger nutrient inflows are expected to shift productivity from benthic microbial mats to planktonic communities, reduce light for phyto benthos, alter biodiversity across trophic levels, and accelerate greenhouse gas emissions [99]. Ground thaw further destabilizes pond persistence: some shallow ponds drain while others persist depending on depth and ground ice. Where snowmelt fails to replenish storage, ponds may vanish and be replaced by wet or dry meadows, with cascading effects on greenhouse gas fluxes, water chemistry, and migratory bird habitats [100]. The groundwater-specific challenges are shown in Figure 5, highlighting reduced recharge, evapotranspiration increases, and permafrost thaw impacts on aquifer flows. Table 2 summarizes the habitat-based overview of climate-induced stressors on freshwater systems, illustrating key mechanisms and their ecological and hydrological consequences.

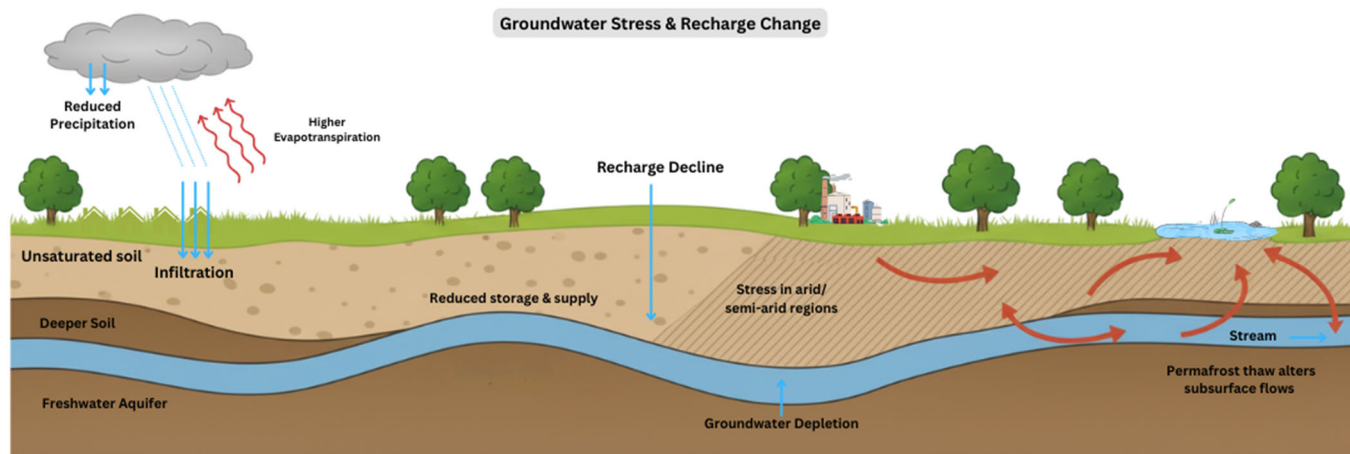


Figure 5. Schematic diagram that illustrates groundwater stress and recharge change. (Conceptual illustration initially AI-generated using OpenAI DALL·E 3 and manually refined in Canva).

3.4. Implications for Water Management

Climate change is intensifying pressure on global water systems, threatening their availability, quality, and reliability. Altered precipitation patterns, rising temperatures, and increasing sea levels are disrupting traditional hydrological processes and challenging existing water management structures. These impacts are especially acute in regions already facing water stress, such as arid and semi-arid zones, coastal areas, and agricultural hotspots. Effective and adaptive management strategies are essential to safeguard water resources, ensure equitable access, and sustain ecosystem services.

Table 2. Habitat-Based Overview of Climate-Driven Impacts on Freshwater Systems.

Habitat/System	Climate Change Effects	Key Consequences	References
Rivers	Altered precipitation and snowmelt timing; stream warming of 0.22 °C/decade in NW U.S.; increased rainfall extremes in Asia and Europe	Earlier and more intense flows, flood risk, habitat loss for salmonids, reduced summer streamflow, altered irrigation reliability	[14,18,23–32,72,79,80,82]
Lakes (deep and large)	LSWT rise ~0.34 °C per decade globally; stronger stratification; hypoxia; more frequent heatwaves; increased algal blooms; reduced ice cover in >5000 lakes	Oxygen depletion, fish die-offs (6–34× increase projected), reduced cold-water habitats, expansion of warm-water fish, trophic instability	[8,11,16,21,22,67,68,74,101–105]
Shallow Lakes	Strong surface-to-volume coupling makes them sensitive to rainfall/runoff; warming lowers nutrient thresholds for eutrophication; rainfall extremes disrupt stratification	Cyanobacterial blooms, oxygen stress, destabilized food webs, biodiversity loss (fish and zooplankton decline, phytoplankton increase)	[84,85,87–93]
Ponds	Sensitive to evaporation and rainfall timing; permafrost thaw causing drainage; heat extremes up to 40–45 °C; shortened hydroperiods	Disappearance in Arctic/Subarctic, biodiversity decline, disease transmission rise (parasites in snails, amphibian deformities), aquaculture threats	[92–100]
Wetlands	Increased evapotranspiration; drought-driven respiration > production; altered precipitation balance	Carbon release (sink → source), habitat degradation, loss of biodiversity	[7,101]
Groundwater	Declining recharge in arid/semi-arid zones; permafrost thaw altering flows; over-extraction worsens stress	Lower water tables, salinization, quality degradation, destabilized aquifers	[43–46]

3.4.1. Climate Change and Water Management Strategies

Climate change has introduced new complexities in water management, particularly in urban areas. Many urban areas still lack climate-resilient planning frameworks, leaving infrastructure and water systems vulnerable. Integrating adaptation measures into urban and regional planning is critical to enhancing resilience and ensuring the sustainable delivery of water services [106–108]. Uncertainty in predicting the future impacts of climate change on agriculture, urban infrastructure, and ecosystems complicates water management strategies. Uncertainty surrounding the future magnitude and distribution of climate impacts further complicates planning efforts. Projections related to agriculture, hydropower, and ecosystem dynamics remain variable, demanding flexible and evidence-based management approaches. For example, Iran’s Urmia Lake Basin, where rising temperatures and declining rainfall are projected to reduce streamflow and elevate evapotranspiration. Adopting strategies such as crop diversification and improved irrigation efficiency can reduce vulnerability and support agricultural and environmental sustainability [109–111].

In mountainous regions like the Swiss Alps, climate-induced shifts in seasonal discharge patterns such as rising winter flows and reduced summer availability pose new risks, including flooding, landslides, and seasonal water deficits. Adaptive governance and multi-sector coordination are needed to address competing demands from hydropower, agriculture, and tourism. Globally, declining water availability in already stressed regions will require expanded forecasting capacity, demand management, and infrastructure upgrades. For example, in Canada’s Black River watershed, increased winter precipitation and early snowmelt are accelerating phosphorus loading in surface waters, threatening water quality. Future strategies must include nutrient management during high-flow periods to protect freshwater ecosystems [112,113].

Forecasts of sub-basins of the Upper Blue Nile Basin, such as the Main Beles and Gilgel Beles suggest, regional temperature increases of up to 3.6 °C by century's end, driving an estimated 8% rise in potential evaporation. While dry-season rainfall may slightly increase, critical wet-season flows could decline by up to 19%. These changes threaten farming systems dependent on consistent wet-season flows, underscoring the need for improved irrigation infrastructure and enhanced water storage techniques to buffer against variability [114]. Southern European basins face similar concerns, with climate models predicting significant declines in water availability. Region-specific solutions such as diversifying water sources, optimizing allocations for environmental flows, and investing in infrastructure will be essential [115,116]. In South Asia, especially in countries like Nepal, integrating groundwater and surface water sources into irrigation systems will be key to supporting dry-season agriculture [117]. At the same time, changes in land-use and climate are increasing nutrient runoff, raising concerns over water quality in agricultural areas. Promoting sustainable practices like conservation tillage and crop rotation will be critical to addressing these pressures [118–120]. Low-lying regions such as the Ganges Delta face additional stress from saltwater intrusion and poor drainage. Managing water and salt balances through controlled pumping, efficient drainage, and monitoring systems is essential for food and water security in such vulnerable zones [121].

Overall, climate change is reshaping water availability and quality through both gradual and extreme changes. Rising sea levels, increased evaporation, and intensifying floods are contaminating water sources and disrupting distribution. Water management systems must therefore evolve to integrate resilience, adaptability, and sustainability across urban, agricultural, and natural ecosystems [122–124].

3.4.2. Role of Emerging Technology in Water Management

The recent advancement of various machine learning models, artificial intelligence, risk assessment strategies, remote sensing and geospatial techniques has significantly enhanced water management strategies by enabling improved monitoring, modeling, analysis and simulation for water management in response to climatic change. Deep learning models such as Long Short Term Memory (LSTM) can effectively capture temporal hydrological and climate time series data which is useful for forecasting rainfall and predicting hydrodynamics processes [125,126]. Combination of physical models with machine learning models even advances water management through more accurate forecasting. For example; a study in arid and semi-arid region applied MODFLOW for flow simulation, K-means clustering for classification of similar ground water level area and ANN for prediction of ground water levels with high accuracy which is essential for ground water management in changing climatic conditions [127]. Thermal models such as Flake is instrumental in identifying key factors that govern lake warming, including depth, albedo, and wind dynamics [14,110]. The integration of Internet of Things (IoT) sensors with Artificial Intelligence (AI) enables real-time monitoring of water temperature, pH values, dissolved oxygen levels, and pollutants, allowing for the early detection of sudden anomalies in water bodies and facilitating water quality management [128,129]. Through the implementation of Geo-AI and autonomous satellite image analysis, a study in Ukraine successfully identified safe drinking water sources, exceeded water pollution, average annual river swallowing and cases of oil pollution [130]. Satellite observations can further be used to show the lake heatwaves, periods of abnormally high LSWT [103–105]. By analyzing changes in backscatter values from ASCAT remote sensing data, combined with precipitation, temperature, and streamflow modeled using the Glacio-Hydrological Degree-Day Model (GDM), researchers were able to estimate ice melting duration and quantify the contributions of snowmelt, ice melt, rainfall, and baseflow to river flow [131]. Such insights are crucial for improving

flood forecasting, optimizing reservoir operations, and ensuring sustainable water resource management in glacier-fed river basins. Additionally, the extraction of water bodies using object-based methods, along with the calculation of water indices such as the Normalized Difference Water Index (NDWI) from 10 m resolution Sentinel-2 optical imagery, and thresholding approaches applied to Sentinel-1 GRD data can support sustainable water resource planning [132,133].

While advanced modeling and monitoring tools enhance understanding of hydrological processes, their true value lies in application to disaster risk reduction, particularly in classifying high-risk zones and guiding targeted interventions. Several recent studies have employed machine learning models utilizing hydrological parameters to assess flood susceptibility zones, enabling targeted interventions [134,135]. To further enhance water management and ecosystem protection, GIS-based risk assessment provides a comprehensive framework for integrating socio-economic and hydrological data, enabling precise identification of vulnerable areas and guiding targeted mitigation strategies that safeguard both communities and natural resources [136,137]. The summary of emerging technologies and tools applied in water management is presented in Table 3, highlighting their core focus, benefits, and associated challenges.

Table 3. Technological Tools in Water Management: Core Focus, Benefits, and Challenges.

Tools	Core Focus	Benefits	Challenges	Reference(s)
Machine Learning and Deep Learning	Forecasting rainfall, hydrodynamics, groundwater levels, flood susceptibility mapping	Improved accuracy in predicting water flow and flood-prone zones	Requires large datasets, computational resources, and model calibration complexities.	[126,134]
IoT and Geo-AI with Remote Sensing	Real-time water quality monitoring, mapping water bodies, detecting pollution, analyzing glacier melt	Early detection of anomalies; large-scale monitoring	sensor deployment and maintenance costs; data processing complexity; cloud cover and spatial and temporal resolution issues	[129,130,132]
GIS-based Risk Assessment and Integrated Models	Integrating socio-economic, hydrological, and environmental data for flood risk and vulnerability assessment	Identifies high-risk areas; guides targeted mitigation	Data availability and quality; requires stakeholder engagement	[136,137]

3.4.3. Adaptive Strategies for Water Management

Adapting to the impacts of climate change on water systems requires a combination of nature-based, infrastructure-focused, and policy-driven strategies. Among these, Integrated Water Resource Management (IWRM) plays a central role by promoting coordinated development and management of water, land, and related resources [138,139]. IWRM ensures that water use is optimized to support economic growth, environmental protection, and social equity particularly in regions facing intense hydrological stress [140]. In addition to IWRM, a nexus approach is increasingly recognized as essential for climate-resilient adaptation. Rooted in IWRM but extending beyond water, the water–energy–food–ecosystem (WEFE) nexus emphasizes cross-sectoral planning and co-benefits [141]. Case studies illustrate its potential: in South Africa, nexus strategies such as promoting drought-tolerant indigenous crops, improving irrigation efficiency with solar-powered systems, and expanding renewable energy help reduce resource pressures and strengthen resilience [142]. In the Hindu Kush Himalaya (HKH) region, improving freshwater use efficiency not only eases food, water, and energy stresses but also addresses poverty and inequality, thereby enhancing long-term sustainability [143].

Ecosystem-based adaptation (EbA) approaches are equally vital. These strategies leverage the natural functions of ecosystems such as wetlands, forests, and mangroves to regulate water flow, water quality, buffer against floods and droughts and support biodiversity [144]. EbA not only strengthens ecological resilience but also provides co-benefits like carbon sequestration, improved water quality, and livelihood support. However, challenges remain in implementing EbA, especially in under-resourced regions that lack technical capacity and long-term financing [145].

Infrastructure upgrades complement IWRM and EbA by enhancing the physical capacity of water systems to withstand climate extremes. Investments in green infrastructure such as urban forests, permeable pavements, and restored riverbanks, improve storm-water retention, reduce urban flooding, and promote groundwater recharge. In urban areas, combining grey and green infrastructure can enhance water system resilience while supporting climate-smart development [146–149]. Urban adaptation planning must prioritize baseline data collection, clear implementation strategies, and coordination across policy domains. For example, the integration of EbA into municipal planning can reduce flood risks and heat stress while fostering healthier urban environments. Yet, many adaptation plans lack sufficient technical grounding, limiting their effectiveness [150]. In low-income and climate-vulnerable countries, National Adaptation Programmes of Action (NAPAs) increasingly recognize the importance of nature-based solutions. Many of these nations depend on ecosystems for water regulation and agricultural productivity. However, institutional priorities still often favor hard infrastructure over ecosystem restoration. Scaling up ecosystem-based approaches will require greater international support, knowledge sharing, and sustained investment [151].

In sum, a hybrid strategy combining IWRM, EbA, and infrastructure modernization offers a robust framework for managing water in a changing climate. These strategies not only enhance the resilience of water supply systems but also foster co-benefits for biodiversity, human health, and long-term sustainability. As shown in Table 4, adaptive strategies range from integrated water governance to ecosystem-based interventions and infrastructure improvements, each offering unique benefits and facing specific implementation barriers. These approaches must be strategically combined and contextually tailored to enhance climate resilience across sectors. The integrative pathways from climate change drivers to hydrological processes, ecosystem impacts, and adaptive management options are synthesized in Figure 6. It provides a schematic overview of how climate change drivers cascade through hydrological and ecological processes to affect water systems and management responses. The Sankey diagram visualizes the links from key climatic drivers, such as rising air temperature, precipitation change, and snow-to-rain shifts to physical processes like lake warming, altered runoff, and stratification. These processes influence various subsystems (rivers, wetlands, and lakes), which in turn produce ecosystem and societal impacts, including reduced water quality, altered flow regimes, and biodiversity loss. The final segment of the diagram illustrates adaptive management responses such as Integrated Water Resources Management (IWRM), green–grey infrastructure, and nutrient controls. Conceptually, this framework aligns with the DPSIR model (Drivers-Pressures-State-Impact-Response), where climate drivers act as “pressures” on hydrological states, generating ecological and socio-economic impacts that require adaptive “responses.” This conceptual linkage clarifies the feedback pathways between climate forcing, ecosystem change, and management intervention, strengthening the bridge between scientific evidence and policy implementation.

Table 4. Summary of major adaptive water management strategies in response to climate change, including their key benefits, implementation challenges.

Strategy	Core Focus	Benefits	Challenges	Reference(s)
Integrated Water Resource Management (IWRM)	Coordinated management of water, land, and resources	Balances social, economic, and environmental needs	Requires institutional coordination and capacity	[138–140]
Nexus Approach	Integration of water, energy, food, and ecosystems beyond traditional water-centric planning	Optimizes resource use across sectors, reduces trade-offs and promotes co-benefits, enhances resilience to climate stress and addresses poverty and inequality in vulnerable regions	Requires cross-sectoral coordination, complex governance and institutional barriers and data and capacity gaps in developing regions	[141–143]
Ecosystem-based Approaches (EbA)	Use of natural ecosystems (e.g., wetlands, forests) to buffer climate impacts	Enhances biodiversity, improves resilience, cost-effective	Data scarcity, underfunding, limited integration into planning	[148–151]
Infrastructure Upgrades	Grey and green infrastructure to improve water retention and urban resilience	Reduces flood risk, manages runoff, provides co-benefits (e.g., cooling)	High initial costs, uneven access in under-resourced regions	[146,150,151]
Urban Green Solutions	Green roofs, permeable pavements, urban forests	Mitigates heat islands, improves water infiltration	Lack of baseline data, implementation hurdles	[150]
Crop Pattern Modification	Shift to less water-intensive crops	Enhances water-use efficiency in agriculture	May affect food production patterns and farmer acceptance	[110]
Managed Aquifer Recharge (MAR)	Recharging groundwater to counteract salinization and over-extraction	Secures freshwater supply, buffers drought	Technical complexity, site-specific hydrogeological requirements	[122,152]
Policy and Governance Reform	Cross-sectoral coordination, flexible adaptation frameworks	Enables integrated, long-term planning	Political resistance, institutional inertia	[106,153]

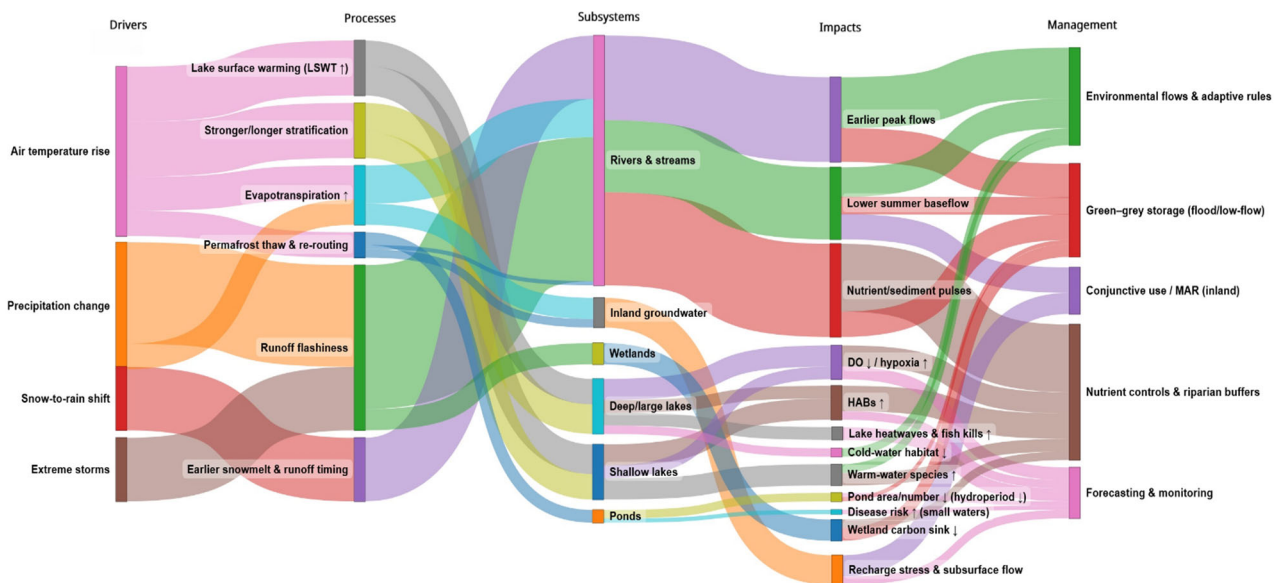


Figure 6. Sankey diagram illustrates the pathways from climate change drivers to hydrological processes, ecosystem impacts, and adaptive management strategies, bridging scientific evidence and policy implications. (Conceptual illustration initially AI-generated using OpenAI DALL·E 3 and manually refined in Canva).

3.5. Policy Relevance and Use for Decision-Makers

This analysis centers on the real concerns facing water agencies: how warming is changing lake and reservoir behavior, how climate change is changing flows and storage, where coastal aquifers are most vulnerable, and which management approaches are supported by data. The report transforms a vast research space into a map that is ready for decision-making by grouping the literature into those six useful themes and limiting the corpus to current, peer-reviewed work (2010–2025). More volatile precipitation and earlier snowmelt, warmer and more strongly stratified lakes with higher harmful-algal-bloom risk are consistent signals that the hydrology and thermal sections translate into policy-actionable issues, such as reservoir rule curves and seasonal allocation, flood and drought design standards, water-quality objectives, and thermal discharge limits. By highlighting areas where drinking water sources, wellfields, and wetlands are likely to require protection or alternate supplies, the coastal portion does the same for sea level rise and saline intrusion.

In addition, the adaptation and governance section connects options to the environments in which they typically function best: nature-based solutions for low-regret flood and water-quality benefits, managed aquifer recharge for drought buffering and salinity control, and integrated water resources management for basin-scale coordination. This allows planners to build portfolios rather than relying solely on one tool. In order to assist agencies, modernize without waiting for ideal data, the emerging-technologies section demonstrates how remote sensing, GIS, and machine learning are already being utilized for monitoring, early warning, and investment targeting. The evaluation provides ministries, basin authorities, and utilities with a clear shortlist for additional monitoring or investigations by keeping the evidence arranged by system, driver, and response. It also highlights gaps in geographic coverage, metrics, and time periods. To put it briefly, the document offers a current body of evidence that is connected to actual policy levers and can be used to drive national adaptation processes, urban water strategies, and basin plans. It does so in a fashion that is easy to update as new findings become available and that can be traced and cited.

4. Conclusions

This review shows that climate change is fundamentally altering freshwater systems rivers, lakes, ponds, wetlands, and groundwater with clear and measurable consequences across all climatic regions. Warming has intensified hydrological variability, leading to earlier snowmelt, more erratic precipitation, and higher stream temperatures. Across mountain catchments and mid-latitude basins, wet-season flows are projected to decline by up to one-fifth under high-emission scenarios, while glacier-fed systems show warming trends of roughly +0.2 to +0.4 °C per decade (e.g., Hindu Kush Himalaya). Lakes worldwide exhibit consistent thermal increases of approximately +0.3 °C per decade, with extremes exceeding +0.5 °C in some temperate regions (e.g., deep European lakes). These shifts reduce ice cover duration, weaken vertical mixing, and threaten aquatic oxygen and biodiversity. Shallow lakes and ponds are especially vulnerable, with Arctic ponds shrinking by more than 30% in recent decades and semi-arid Asian ponds projected to shorten their water-filled season by nearly a month by 2080. Wetlands, which store up to a third of the world's soil carbon, are beginning to release more carbon than they capture under drought conditions in Mediterranean and South Asian regions. Groundwater resources, already stressed, are declining further as glacier retreat reduces recharge, such as in Afghanistan's Kokcha sub-basin where glacier area has fallen by ~15%, while over-extraction in South Asia and the Mediterranean worsens scarcity and salinization.

The way forward is to adapt with solutions tailored to both habitat and region, framed by the water–food–energy–ecosystem nexus. In flood-prone river basins like Eastern Africa and South Asia, adaptive reservoirs, green–grey flood defenses, and real-time forecasting through IoT and machine learning can reduce disaster risks while protecting agriculture and energy systems. In glacier-fed catchments such as the Himalayas and the Alps, early warning systems and satellite monitoring are essential to safeguard communities and hydropower from sudden floods. In biodiversity-rich lakes and wetlands of Europe, the Arctic, and Africa, ecosystem-based strategies such as riparian restoration, nutrient management, and wetland conservation can build resilience while maintaining food and habitat security. In water-scarce regions like the Mediterranean and South Asia, precision irrigation, smart groundwater management, and climate-informed modeling can optimize use while easing pressure on ecosystems.

In sum, climate change is transforming freshwater systems in ways that differ by habitat and region, but everywhere the impacts are quantifiable and increasingly urgent. Building resilience means addressing water not in isolation but as part of the broader nexus that links it with food, energy, and ecosystems. By sharing data and coordinating actions across borders, societies can design solutions that are regionally relevant, globally connected, and sustainable for both people and nature.

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