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Climate Change and Aquatic Ecosystem Health: Impacts, Adaptation Strategies, and Future Challenges

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Abstract Aquatic ecosystems, such as rivers, lakes, wetlands, and oceans, rely on stable climatic conditions to maintain their complex biological networks and ecological functions. However, as global temperatures rise, precipitation patterns change, and ocean acidification intensifies, these systems are facing unprecedented challenges. This study provides a detailed analysis of the impacts of climate change on water temperature, ocean acidification, the hydrological cycle, and biodiversity. It highlights the potential risks to sensitive ecosystems and vulnerable species and proposes adaptation strategies, including the establishment of marine protected areas, the application of habitat restoration techniques, and measures to enhance ecosystem resilience. Through multiple successful case studies, the study summarizes key lessons learned in climate change adaptation and points to future research directions. This research contributes to a deeper understanding of the mechanisms by which climate change impacts aquatic ecosystems, providing a scientific basis for the protection and restoration of these systems, thereby promoting the achievement of sustainable development goals.

Keywords Climate change; Aquatic ecosystems; Ecosystem resilience; Ocean acidification; Sustainable development goals (SDGs)

1 Introduction

Climate change is an unprecedented global phenomenon driven predominantly by human activities, leading to significant alterations in environmental conditions across the planet. Aquatic ecosystems, encompassing both freshwater and marine environments, are particularly vulnerable to these changes. The impacts of climate change on these ecosystems are multifaceted, including increased water temperatures, altered precipitation patterns, and rising sea levels, which collectively disrupt the delicate balance of aquatic habitats (Häder and Barnes, 2019). For instance, many lakes are experiencing shorter ice cover periods and longer summer stratified seasons, resulting in warmer water temperatures and reduced dissolved oxygen levels, which can lead to harmful algal blooms and loss of habitat for cold-water species (Woolway et al., 2022). Similarly, coastal ecosystems are facing threats from sea level rise and increased storm intensity, which jeopardize the livelihoods of communities dependent on these ecosystems.

The health of aquatic ecosystems is crucial for maintaining biodiversity, ensuring water quality, and providing essential ecosystem services that support human well-being. These ecosystems are integral to the global water cycle, nutrient cycling, and carbon sequestration, and they offer habitat for a wide range of species, including those critical for fisheries and aquaculture (Griffith and Gobler, 2020; Pandit and Sharma, 2023). Aquatic ecosystems contribute to cultural and recreational values and are vital for the livelihoods of millions of people worldwide. The degradation of these ecosystems due to climate change can lead to significant socio-economic consequences, including reduced food security, increased prevalence of water-borne diseases, and loss of income from tourism and fisheries (Hernández-Delgado, 2015; Pecl et al., 2017).

This study aims to comprehensively analyze the impacts of climate change on aquatic ecosystem health, explore adaptation strategies that can mitigate these impacts, and identify challenges that need to be addressed in the future. By synthesizing current knowledge, this study will highlight the direct and indirect impacts of climate change on aquatic communities, habitats, and ecosystem functions, examine and provide insights into the effectiveness of various adaptation strategies implemented in different regions and ecosystems, and discuss key knowledge gaps and research needs that must be addressed to enhance our understanding and management of aquatic ecosystems under current and future climate change scenarios.

2 Impacts of Climate Change on Aquatic Ecosystems

2.1 Temperature variations and thermal stress

2.1.1 Effects on fish physiology and behavior

Climate change has led to significant increases in water temperatures, which directly affect fish physiology and behavior. Elevated temperatures can alter fish metabolism, growth rates, and reproductive cycles. For instance, fish species in subarctic freshwater ecosystems are experiencing changes in their behavior, habitat use, and growth due to increased ambient water temperatures (Rolls et al., 2017). Fish are undergoing evolutionary adaptations to cope with temperature extremes, which include changes in tolerances to high temperatures and shifts in sex ratios in species with temperature-dependent sex determination (Scheffers et al., 2016).

2.1.2 Changes in metabolic rates

Increased water temperatures result in higher metabolic rates in fish, which can lead to increased energy demands and altered feeding behaviors. Studies have shown that the overall effects of climate change on fish growth are predominantly negative, with higher temperatures leading to increased metabolic costs and reduced growth rates (Menden-Deuer et al., 2023). This is particularly evident in freshwater ecosystems, where fish are less studied compared to their marine counterparts, but the negative impacts on physiology and health are consistent across different species and habitats (Huang et al., 2021).

2.1.3 Shifts in species range and distribution

As water temperatures rise, many fish species are shifting their geographic ranges to maintain their preferred environmental conditions. This often involves moving poleward or to higher elevations in search of cooler waters. Such shifts can lead to changes in species distribution and abundance, with warm-adapted species expanding their ranges and cold-adapted species experiencing range contractions (Scheffers et al., 2016; Pecl et al., 2017). These distributional changes can disrupt existing ecological communities and lead to the formation of novel biotic interactions.

2.2 Alterations in hydrological cycles

Climate change is also modifying hydrological cycles, affecting the availability and distribution of freshwater resources. Changes in precipitation patterns, streamflow, and water levels are altering the hydrological regimes of aquatic ecosystems. For example, subarctic freshwater ecosystems are experiencing increased nutrient availability and shortened ice cover periods, which impact the ecological responses of freshwater fishes. These alterations can lead to changes in spawning and recruitment dynamics, ultimately affecting species abundance and distribution (Rolls et al., 2017).

2.3 Ocean acidification and its consequences

Ocean acidification, driven by increased atmospheric CO_2 levels, is another significant impact of climate change on aquatic ecosystems. Acidification affects the physiology and behavior of marine organisms, particularly those with calcium carbonate structures, such as corals and shellfish. The combined effects of warming, acidification, and deoxygenation are intensifying the impacts of harmful algal blooms (HABs) in marine and freshwater ecosystems, further stressing aquatic organisms (Figure 1) (Griffith and Gobler, 2020). These changes can have cascading effects on food webs and ecosystem services.

Harmful algal blooms not only release toxins that are harmful to humans and other organisms but also lead to a reduction in dissolved oxygen in the water, creating low-oxygen or even hypoxic zones, which can be fatal for aquatic organisms that rely on oxygen for survival. As climate change intensifies, the frequency and severity of these harmful algal blooms are likely to increase further, particularly in water bodies already affected by pollution and eutrophication, such as coastal areas and freshwater lakes. Research has shown that in environments with high carbon dioxide concentrations, the toxicity of some algae may increase, leading to more widespread biological deaths. Warming may also promote the vertical migration of harmful algal blooms, making them more likely to reach the ocean surface and aquaculture areas, thereby increasing the exposure risk for aquatic organisms.

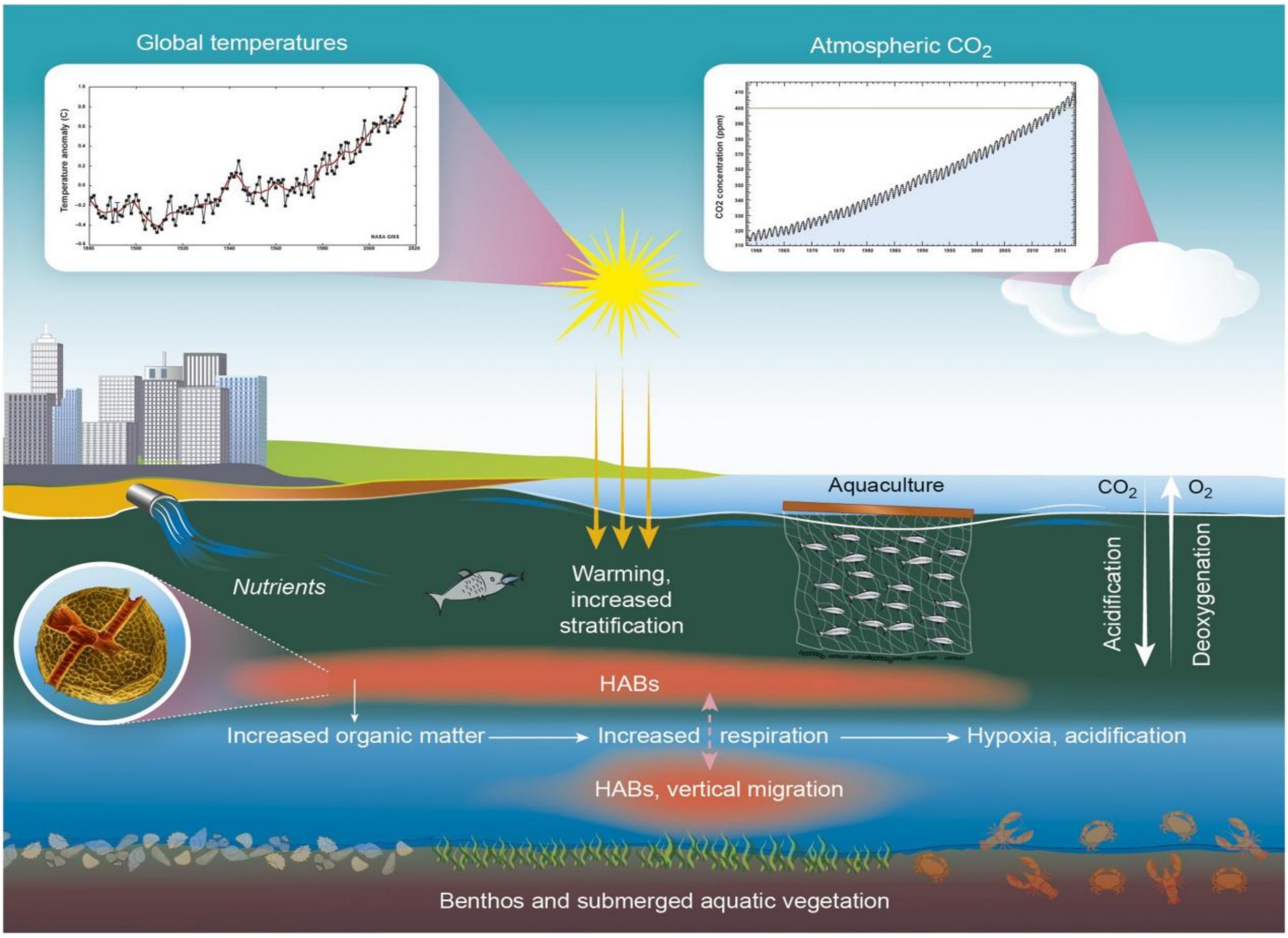

Figure 1 The impact of climate change on aquatic ecosystems (Adopted from Griffith and Gobler, 2020)

2.4 Impact on biodiversity and species distribution

Climate change is causing widespread shifts in species distributions, leading to changes in biodiversity and ecosystem structure. As species move to new areas, they can disrupt existing ecological interactions and create novel communities. This redistribution of species can have profound effects on ecosystem functioning and human well-being (Pecl et al., 2017). For instance, the redistribution of fish species in North America due to climate-induced changes in water temperature and salinity can lead to fish extinctions, invasions, and altered community structures. These changes highlight the need for adaptive management strategies to mitigate the impacts of climate change on aquatic biodiversity and ecosystem health (Paukert et al., 2021).

3 Vulnerability of Aquatic Ecosystems

3.1 Sensitive ecosystems: coral reefs, wetlands, and estuaries

Sensitive ecosystems such as coral reefs, wetlands, and estuaries are particularly vulnerable to the impacts of climate change. Coral reefs, for instance, are facing significant threats from rising sea surface temperatures and ocean acidification. Even under lower greenhouse gas emission scenarios, most warm-water coral reefs are projected to be eliminated by 2040~2050. Cold-water corals are also at risk, although the direct effects of climate change on these ecosystems are less clear (Hoegh-Guldberg et al., 2017). Estuaries, which are critical for various species and ecological processes, are similarly vulnerable. Climate change impacts such as altered river flows, increased storm frequency, and sea-level rise are expected to significantly affect estuarine hydrology and species distribution. Wetlands, which provide essential services such as water filtration and habitat for numerous species, are also at risk due to changes in precipitation patterns and sea-level rise (Farr et al., 2021).

3.2 Vulnerable species and habitats

The vulnerability of species and habitats to climate change varies widely. In the Pacific Islands region, a vulnerability assessment identified invertebrates as the most vulnerable group, while pelagic and coastal species not associated with coral reefs were the least vulnerable (Giddens et al., 2022). Species with complex life histories, habitat specialization, long lifespans, and low population growth rates are particularly at risk (McClure et al., 2023). For example, the Hilsa fish in the Meghna estuary is significantly affected by climate-forced hydrological changes, impacting its population and the local economy. Habitats such as coastal and riverine areas are highly vulnerable due to the combined effects of climate change and anthropogenic stressors.

3.3 Ecosystem services at risk

Climate change poses a significant threat to the ecosystem services provided by aquatic ecosystems. Coral reefs, for example, offer food, income, coastal protection, and other services to approximately 500 million people globally. The degradation of these reefs due to climate change could lead to increased poverty and social disruption. Similarly, coastal ecosystems in small tropical islands, which provide essential services such as protein sources, building materials, and tourism revenue, are declining due to climate change (Hernández-Delgado, 2015; Hoegh-Guldberg et al., 2017). Estuaries also provide critical services, including supporting fisheries and maintaining water quality. The impacts of climate change on these ecosystems could disrupt these services, leading to broader ecological and socio-economic consequences (Filho et al., 2022).

4 Adaptation Strategies for Aquatic Ecosystems

4.1 Conservation and restoration efforts

4.1.1 Marine protected areas (MPAs)

Marine Protected Areas (MPAs) are a critical tool in the conservation and restoration of marine ecosystems. They serve to mitigate the impacts of climate change by providing refuges where marine life can thrive without the pressures of human activities such as fishing and habitat destruction. However, the effectiveness of MPAs under climate change is a subject of ongoing research and debate. Studies have shown that while MPAs can enhance ecosystem resilience, their static nature may limit their effectiveness as species distributions shift due to changing ocean conditions (Bruno et al., 2018; Tittensor et al., 2019). To address these challenges, it is recommended that MPAs incorporate climate-responsive design and management, including dynamic management tools and climate-smart objectives (Wilson et al., 2020). Additionally, the integration of MPAs with other management strategies, such as marine spatial planning and stakeholder participation, is crucial for maximizing their resilience and effectiveness.

4.1.2 Habitat restoration techniques

Habitat restoration is another vital strategy for enhancing the resilience of aquatic ecosystems. Techniques such as coral transplantation and artificial reef deployments have shown promise in restoring degraded habitats, particularly for cold-water corals (CWCs) (Montseny et al., 2021). These restoration efforts are essential for ecosystems that are highly vulnerable to climate change and other anthropogenic stressors. However, the success of these techniques depends on a thorough understanding of the biological and ecological characteristics of the target species and habitats. Long-term monitoring and a combination of active and passive restoration approaches are recommended to ensure the sustainability and effectiveness of restoration efforts.

4.1.3 Community involvement and stakeholder engagement

Community involvement and stakeholder engagement are critical components of successful conservation and restoration efforts. Engaging local communities in the management and monitoring of MPAs and restoration projects can enhance the legitimacy and effectiveness of these initiatives. Stakeholder participation ensures that management strategies are socially acceptable and culturally relevant, which is particularly important in coastal social-ecological systems. Collaborative governance approaches that integrate scientific knowledge with local and traditional knowledge can lead to more adaptive and resilient management practices (Schmidt et al., 2022).

4.2 Enhancing ecosystem resilience

Enhancing the resilience of aquatic ecosystems to climate change involves a multifaceted approach that includes reducing local stressors, protecting biodiversity, and promoting adaptive management practices. MPAs play a significant role in this regard by providing areas where ecosystems can recover and maintain their ecological functions (Bates et al., 2019; Smith et al., 2023). However, the resilience of MPAs to climate change is not guaranteed, and their effectiveness can vary depending on the specific characteristics of the protected area and the nature of the climate impacts. Therefore, it is essential to incorporate resilience thinking into the design and management of MPAs, including the identification of climate refugia and the use of adaptive management strategies.

4.3 Sustainable fisheries management

Sustainable fisheries management is crucial for maintaining the health and resilience of aquatic ecosystems. Overfishing and destructive fishing practices can exacerbate the impacts of climate change by reducing the abundance and diversity of marine species. Implementing sustainable fishing practices, such as catch limits, gear restrictions, and the protection of critical habitats, can help mitigate these impacts and support the recovery of fish populations (Harvey et al., 2018; Sala and Giakoumi, 2018). Integrating fisheries management with broader ecosystem-based management approaches can enhance the overall resilience of marine ecosystems to climate change.

5 Mitigation Measures

5.1 Reducing greenhouse gas emissions

Reducing greenhouse gas emissions is a critical step in mitigating climate change and protecting aquatic ecosystems. Marine reserves, when well-managed, can play a significant role in this effort. They help marine ecosystems and human communities adapt to climate change impacts such as acidification, sea-level rise, and shifts in species distribution. Additionally, these reserves promote carbon sequestration and storage, making them a cost-effective adaptation strategy with multiple co-benefits (Roberts et al., 2017). Furthermore, blue carbon ecosystems, including tidal marshes, mangroves, and seagrass meadows, are vital in sequestering carbon. These ecosystems contribute significantly to carbon burial in marine sediments, which is crucial for reducing atmospheric CO_2 levels (Serrano et al., 2019).

5.2 Promoting renewable energy in coastal areas

Promoting renewable energy in coastal areas is another effective strategy for mitigating climate change. Coastal regions are ideal for the deployment of renewable energy sources such as wind, solar, and tidal energy. These renewable energy projects can reduce reliance on fossil fuels, thereby decreasing greenhouse gas emissions. Additionally, integrating renewable energy initiatives with coastal management practices can enhance the resilience of coastal ecosystems. For instance, the development of renewable energy infrastructure can be aligned with the conservation and restoration of blue carbon ecosystems, which further aids in carbon sequestration and climate change mitigation (Bandh et al., 2023).

5.3 Carbon sequestration in aquatic ecosystems

Aquatic ecosystems, particularly blue carbon ecosystems, play a crucial role in carbon sequestration. Mangrove forests, saltmarshes, and seagrass meadows are highly efficient at capturing and storing atmospheric carbon, often at rates much higher than terrestrial forests (O'connor et al., 2019). Restoration and conservation of these ecosystems are essential for maintaining their carbon sequestration capacity. For example, restored blue carbon ecosystems can reach parity with natural sites in terms of carbon stocks after several years, highlighting the importance of long-term management and monitoring. Additionally, wetlands, both inland and coastal, are among the most efficient natural long-term carbon sinks. Despite their methane emissions, the overall net cooling effect of these wetlands makes them valuable for climate change mitigation (Taillardat et al., 2020). The inclusion of macroalgal forests in carbon sequestration efforts also presents a promising avenue, although further research is needed to fully understand their potential (Pessarrodona et al., 2023).

6 Case Studies on Climate Change Adaptation

6.1 Successful adaptation in coastal ecosystems

Coastal ecosystems are particularly vulnerable to the impacts of climate change, including sea level rise, increased storm intensity, and changing ocean temperatures. However, several successful adaptation strategies have been documented. For instance, in Bangladesh, coastal communities have adapted by diversifying their aquaculture practices, such as incorporating crab fattening and improving pond infrastructure, which has helped sustain livelihoods despite the adverse effects of climate change (Hossain et al., 2018). Similarly, the proliferation of sargassum seaweed across the tropical Atlantic has led to the development of national management strategies, open-access knowledge hubs, and innovative clean-up and harvesting equipment, demonstrating effective adaptation to emergent risks (Almela et al., 2023). The incorporation of climate change adaptation into marine protected area (MPA) planning has shown promise, with strategies focusing on climate refugia and adaptive management approaches to ensure the resilience of these critical habitats (Wilson et al., 2020).

6.2 Challenges in river and lake systems

River and lake systems face unique challenges in adapting to climate change. These freshwater ecosystems are experiencing shorter ice cover periods, longer summer stratified seasons, and warmer water temperatures, leading to a cascade of ecological consequences such as reduced dissolved oxygen levels and increased likelihood of harmful algal blooms (Figure 2) (Woolway et al., 2022). The biodiversity crisis in freshwater systems is exacerbated by emerging threats like microplastic pollution, invasive species, and declining calcium levels, which disproportionately impact these ecosystems. Despite these challenges, there are opportunities for conservation gains through novel management tools like environmental DNA and habitat protection policies. However, the implementation of these strategies is often hindered by a lack of comprehensive scientific studies and governance structures that support adaptive management (Reid et al., 2018).

The decline in dissolved oxygen levels is primarily due to the inhibition of vertical water mixing caused by the stratification of warmer water layers during the summer. This leads to the gradual depletion of oxygen in the deeper water layers. This phenomenon is particularly severe in deeper lakes, where the bottom water layers typically rely on seasonal mixing to replenish oxygen. However, as the stratification period lengthens, oxygen replenishment becomes increasingly difficult, and in some extreme cases, lakes may completely lose the ability to replenish oxygen in deep waters. The rise in water temperature also creates more favorable conditions for the outbreak of harmful algal blooms. The frequent occurrence of harmful algal blooms not only severely impacts water quality but also poses a threat to the survival of aquatic organisms. For example, as water temperatures rise, some algae can reproduce more rapidly and form large-scale blooms, which release toxins that further degrade the water environment and reduce dissolved oxygen levels. This situation not only affects fish and other aquatic organisms but also adversely impacts human communities that rely on these freshwater resources.

6.3 Lessons learned from global practices

Global practices in climate change adaptation offer valuable lessons for improving the resilience of aquatic ecosystems. A key finding from studies across multiple coastal communities is the importance of strong, self-organized local institutions in facilitating effective adaptation. Communities with robust local governance structures that set and enforce rules locally and communicate across scales are better able to adapt without substantial loss of well-being (Berman et al., 2019). Additionally, the need for multi-level, multi-sectorial responses is emphasized, particularly in highly vulnerable regions like small tropical islands, where cumulative and synergistic impacts of climate change pose significant challenges. The integration of scientific knowledge into policy and management, as seen in the adaptation strategies for Australian fisheries, highlights the necessity of using evidence-based approaches to inform decision-making processes and ensure the sustainability of these resources (Fogarty et al., 2019; Jiang and Xu, 2024). Successful adaptation in coastal ecosystems, the challenges faced by river and lake systems, and the lessons learned from global practices underscore the complexity and urgency of addressing climate change impacts on aquatic ecosystems. By leveraging local governance, innovative management tools, and evidence-based policies, it is possible to enhance the resilience of these vital ecosystems and the communities that depend on them.

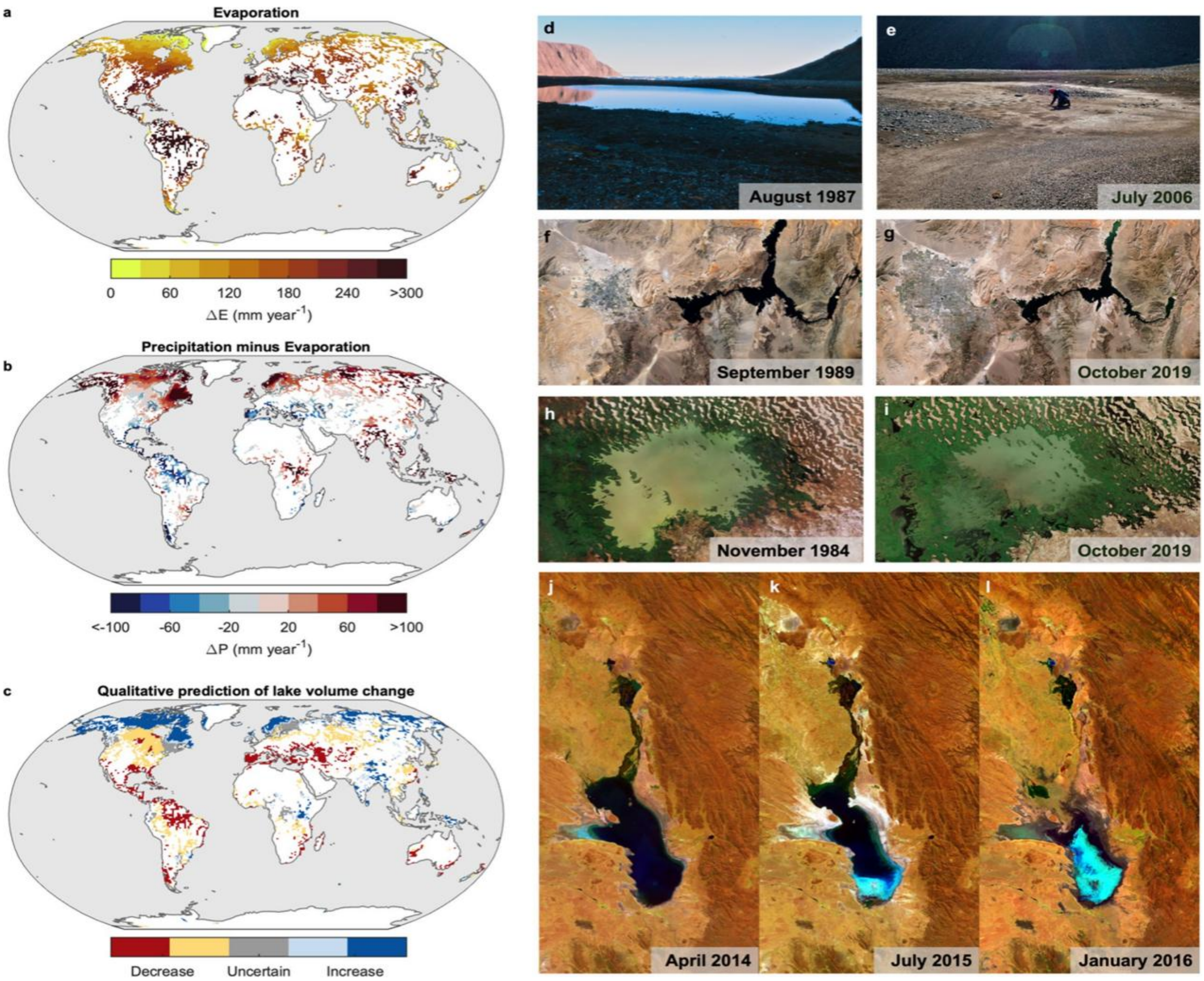

Figure 2 Projected and observed change in water quantity (Adopted from Woolway et al., 2022)

Image caption: Shown are simulated future changes (2071~2100 relative to 1971~2000) in (a) lake evaporation, (b) land P-E (precipitation minus evaporation), and (c) lake volume (based on the P–E balance over land and lake surfaces). Shown in panels (d) and (e) are what were previously permanent High Arctic ponds (Cape Herschel, Canadian High Arctic). (f, g) Satellite images of Lake Mead (United States). (h, i) Satellite images of Lake Chad (bordering Chad, Cameroon, Niger, and Nigeria) (Adopted from Woolway et al., 2022)

7 Future Challenges and Research Directions

7.1 Addressing uncertainties in climate projections

One of the primary challenges in understanding the impacts of climate change on aquatic ecosystems is the inherent uncertainty in climate projections. These uncertainties arise from various sources, including structural (model) uncertainty, initialization and internal variability, parametric uncertainty, and scenario uncertainty. For instance, in marine ecosystems, the degree of attention given to each type of uncertainty varies significantly across subdisciplines, with initialization uncertainty often being neglected (Payne et al., 2016). To improve the robustness of climate projections, it is essential to employ an ensemble approach that includes multiple climate models, land use scenarios, and eco-hydrological models (Trolle et al., 2019). This comprehensive approach can help in better quantifying and communicating the uncertainties, thereby aiding in more effective risk evaluation and confidence building in the projections.

7.2 Integrating climate change into ecosystem management

Effective management of aquatic ecosystems in the face of climate change requires the integration of climate projections into ecosystem management strategies. This involves developing and implementing adaptation strategies that are resilient to the uncertainties of climate impacts. For example, adaptation strategies for coral reef ecosystems in Small Island Developing States (SIDS) have been modeled to integrate local pressures and long-term climate changes, demonstrating the importance of a holistic and systematic understanding of these impacts (Hafezi et al., 2020). Similarly, threshold-based management frameworks have been proposed for freshwater ecosystems to continuously assess and update the susceptibility of ecosystems to climate change, thereby informing policy targets and mitigation measures (Liu et al., 2015). These integrated approaches are crucial for maintaining ecosystem health and the services they provide to society.

7.3 Long-term monitoring and impact assessment

Long-term monitoring and impact assessment are vital for understanding the ongoing and future impacts of climate change on aquatic ecosystems. Continuous monitoring allows for the detection of changes in water quality, biodiversity, and ecosystem services, which are essential for timely and effective management interventions. For instance, the impacts of climate change on water-related ecosystem services in the Jianghuai Ecological Economic Zone, China, were assessed using long-term climate and land use scenarios, highlighting the need for sustainable water resource management (Guo et al., 2021). Systematic reviews of adaptation strategies for water quality management have emphasized the importance of long-term strategic measures to address the significant challenges posed by climate change (Bartlett and Dedekorkut-Howes, 2022). These efforts underscore the necessity of sustained monitoring and assessment to inform adaptive management and policy decisions.

8 Concluding Remarks

Climate change poses significant threats to aquatic ecosystems, impacting biodiversity, ecosystem services, and the livelihoods dependent on these systems. Marine species are adapting to climate change through shifts in distribution and timing of biological events, although evidence for evolutionary adaptation is limited. Human systems show a focus on adaptation planning frameworks, but there is a scarcity of implemented actions and outcome evaluations. Climate change impacts on water quality are under-researched compared to water availability. Adaptation strategies often employ coping or incremental approaches, which may not be sufficient for future challenges. Integrating climate change adaptation into MPA design and management is crucial. Recommendations include adopting climate-smart management objectives and using dynamic management tools to enhance responsiveness. Coral reef ecosystems, particularly in Small Island Developing States (SIDS), face severe threats from climate change. Integrated modelling approaches can help predict future conditions and the success of adaptation strategies. Adaptation in forest management requires understanding climate impacts on forests and incorporating this knowledge into decision-making. Multi-disciplinary approaches and partnerships are essential for effective adaptation. Australian fisheries face challenges from climate change, with a need for more scientific research to inform adaptation initiatives. The use of existing knowledge in decision-making processes is crucial for sustainable fisheries management.

Proactive adaptation strategies are essential to mitigate the adverse effects of climate change on aquatic ecosystems. These strategies should be flexible, dynamic, and based on robust scientific evidence. For instance, the integration of climate change adaptation into MPA management can ensure long-term effectiveness in safeguarding marine biodiversity and ecosystem services. Similarly, proactive measures in forest management and fisheries can help maintain ecosystem health and productivity, thereby supporting the livelihoods that depend on these resources.

To address the challenges that climate change poses to aquatic ecosystems, the following recommendations are made to policymakers and researchers. Policymakers should integrate climate adaptation into policy and ensure that climate-smart management objectives are incorporated into national and international policies for protected areas and natural resource management. Allocate funding and resources to support research on climate change impacts and adaptation strategies and promote the implementation of these strategies. Encourage multi-level, multi-sector responses to enhance the resilience of social-ecological systems, especially in vulnerable areas such as small island developing States. Researchers should expand the scope of their research and address research gaps by focusing on under-researched areas, such as the impacts of climate change on water quality and aquatic environments in specific regions. Conduct research to develop, implement, and evaluate adaptation strategies in different ecosystem and social-ecological contexts. Promote interdisciplinary research that integrates ecological, social, economic, and behavioral sciences to improve decision-making and management practices. By adopting these recommendations, policymakers and researchers can work together to enhance the resilience of aquatic ecosystems and the communities that depend on them in the face of climate change.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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