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Climate change impacts on water resources and emerging strategies for sustainable management

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Abstract: The strong influence of climate change on terrestrial-aquatic ecosystems is illustrated by changes in the hydrological cycle, water quality degradation, and the intensification of extreme events such as floods and droughts. This review brings together the international evidence on the coupled impacts of climatic variability on freshwater availability, pollution, agricultural practices, and governance systems. The results suggest that changes in precipitation regimes, increases in ambient temperatures, and accelerated snowmelt all reduce streamflow and groundwater recharge. These alterations further disturb seasonal water availability, ecosystem services, and the long-term security of communities dependent on freshwater resources. At the same time, anthropogenic pollution and eutrophication are additional threats to aquatic ecosystems. Extreme climatic events increase the risk of flooding and drought, which in turn result in socio-economic losses and reduced agricultural productivity. Fisheries and food systems, more generally, are highly sensitive to increases in temperature and habitat degradation. The review also highlights that vulnerable regions require integrated monitoring, early-warning systems, and locally adaptable mitigation strategies. Good governance, grounded in the principles of equity, inclusion, and adaptive management, is needed for sustainable water allocation and resilience-building. The combination of climate-smart agricultural practices, technological interventions, and transboundary cooperation offers promising ways forward for achieving water sustainability amid future climatic uncertainty. Overall, the study emphasises the need for science-based policy, stakeholder participation, and coordinated international action.

Keywords: climate change, hydrological cycle, sustainability, water quality, water resources

INTRODUCTION

Industrialisation, urbanisation, and climatic variability are placing a serious burden on water resources. Dyes, heavy metals, fertilisers, and pesticides contamination of aquatic ecosystems continues to worsen and threaten human health, thus calling for more urgent improvements in treatment and reuse (Rathi, Kumar and Vo, 2021). High levels of heavy metals in many parts of Asia and Africa have been linked to population pressure and the lack of environmental protection measures (Ismanto *et al.*, 2023). These anthropogenic pressures have increased the rate of groundwater depletion and pollution, making the imperative for integrated water-resource management (Elsaidy *et al.*, 2025).

An integrative understanding of interactions between humans and water, grounded in frameworks that blend the natural and social sciences, is necessary for sustainable water management (Gohari *et al.*, 2025). Transdisciplinary approaches are used to improve governance and resource efficiency by aligning ecological processes with policy and economic instruments (Chowdhary *et al.*, 2020). Climate change adds to the complexity of these dynamics through changes in precipitation, temperature, and land-use patterns. Pollution control and catchment area protection have shown that effective governance measures can significantly improve water quality in different parts of Europe (Hein *et al.*, 2021). Geological formations, agricultural drainage, and landfill leachate also determine pollutant pathways, thus showing the combined effects of natural and anthropogenic factors on hydrological quality (Lin *et al.*, 2010).

The global hydrological cycle involves constant interaction between surface and groundwater systems, which is disturbed by temperature increases and changes in rainfall regimes driven by climate change (Feng *et al.*, 2018). Several case studies worldwide have observed declining river discharge, increasing salinity, and declining snowmelt, all of which affect streamflow and reduce water availability. Such hydrological stress affects irrigation, urban water supply, and aquatic ecosystems, particularly in densely populated or industrialised areas (Beniston and Stoffel, 2014). Adaptive water pricing and conservation policies have been proven effective in strengthening long-term security; however, uncertainties and modelling gaps in local governance remain major challenges (Dawadi and Ahmad, 2013).

Estimates now predict that by 2030, global water demand will outstrip supply by 40%, and close to 1.8 bn people will live in water-stressed regions. Studies at the regional scale, ranging from the Limpopo River Basin in Africa (El-Mahdy, 2022) to the Upper Blue Nile (Mengistu *et al.*, 2021), show an increasing vulnerability of freshwater yields to rising temperatures and variable precipitation. Similarly, the backward irrigation systems in Central Asia and poor drainage in Mediterranean basins continue to contribute to salinisation and ecosystem degradation. These findings highlight the need for locally based but globally integrated systems of sustainable water governance.

In brief, the interlinkages among human pressures, landforms, and governance issues provide the context for how climate change exacerbates water scarcity and pollution. This review summarises global evidence on the multiple impacts of climate change on water resources, including water quality, water scarcity, socio-economic impacts, and governance. It emphasises the need for integrated, adaptive management approaches that reconcile environmental protection and socio-economic development goals within the context of sustainable water and land-use management.

CLIMATE CHANGE AND WATER RESOURCES

The hydrological cycle underpins the availability, quality, and spatial distribution of freshwater resources; however, it is currently undergoing major changes in response to climate change, thereby threatening water security at various spatial scales. Yang, Yang and Xia (2021) summarise this new reality and show how the combined effects of increased temperatures, altered precipitation patterns, increased snowmelt, and altered evapotranspiration reshape water storage and flow regimes globally. Their synthesis highlights four interrelated perspectives – classical water-cycle mechanics, hydrological processes, human-natural coupling, and integrated watershed management – all of which are now coming under stress from climatic forcing.

On the supply side, changes in precipitation and snow-glacier melt have very important consequences. For example, models project that most midlatitude and mountainous areas are experiencing earlier snowmelt and shorter snowpack duration, shifting peak flow timing earlier than the traditional irrigation/consumption season. This change in stream-baseflow dynamics and recharge windows (groundwater) increases vulnerability during dry seasons. Moreover, Fowler *et al.* (2022) identified a surprisingly persistent shift: watersheds experiencing repeated droughts have lower annual streamflow for a given precipitation amount, suggesting that hydrologic system resilience is decreasing (a gap in traditional models that assume stationarity in runoff-precipitation relationships). Groundwater systems are also coming under growing pressure. Although many assessments are conducted on surface flows, the underground compartment is important for maintaining supply during dry spells. Khoi *et al.* (2022) simulated discharge and groundwater recharge in Vietnam and concluded that although recharge might increase under some scenarios, high uncertainty still exists, and many basins could even deplete. Consequently, water managers can no longer make planning decisions based on the assumption that past recharge patterns will continue.

Climate change is also intensifying the hydrological cycle: increased water vapour in the atmosphere, increased evaporation, and more precipitation extremes. Ficklin *et al.* (2022) show that increasing the extremes of wet and dry conditions makes infrastructure and resource design for water systems more challenging. These interactions add to the water-scarce/flood-prone paradox: places may be impacted by both drought and flood with increasing frequency. El Assaoui, Sadok and Merimi (2021) studied Moroccan groundwater resources at the climatic, hydrological, and hydrogeological levels. The software process simulation modelling (SPSM), fifth-generation Penn State/NCAR Mesoscale Model (MM5), and regional climate model (RCM) simulations (e.g., ALADIN-Climat (Fr. acronym: ALADIN – Aire Limitée Adaptation dynamique Développement InterNational) and Modelling System for Agricultural Impacts of Climate Change (MOSAIC)) showed increasing impacts, including saline intrusion, reduced water quality, reduced recharge, and reservoir constraints. Wilk-Woźniak, Krztoń and Górnik (2021) studied the ecological and climatic effects in a deep-dam reservoir in southern Poland over 30 years. Although land-use change and improved watershed management have occurred, global warming prolonged the period of thermal stratification, altering the physical and chemical properties of the reservoir. These findings highlight the complex interaction between socioeconomic development and climate change, which is having a fundamental impact on water systems.

Chakraborti and Shimshack (2022) examined environmental disparities in urban Mexico using nine years of data on toxic water pollution from more than 1,600 industrial plants. Their results showed that low-income neighbourhoods were exposed to higher levels of pollution and that collective action and community pressure played a role in addressing environmental exposure inequities. Tang *et al.* (2022) studied two decades of water pollution control in China, in particular, wastewater treatment plants (WWTPs) in ten major river basins. China's urban and rural treatment rates were over 90%, yet pollution persisted in the eastern river basins, not due to population growth but to economic development. This challenge has been advised to be overcome by improving wastewater collection, strengthening effluent regulation, and expanding treatment capacity.

WATER QUALITY AND POLLUTION

Water pollution is one of the most important threats facing sustainable water management, responsible for more deaths every year than any other environmental hazard. Although freshwater accounts for only one per cent of Earth's total water resources, fast industrialisation, urban expansion, and climate variability continue to deplete this limited resource (Tang *et al*., 2018). Microbial pathogens make the water-quality protection even more difficult. Saingam, Li, and Yan (2020) examined microbial contamination in a tropical urban estuary and found that conventional faecal-indicator bacteria tests underestimate the presence of pathogens. Direct molecular detection of *Vibrio parahaemolyticus*, the predominant risk species, highlighted the need for more sophisticated microbial risk assessment tools. Fang *et al*. (2022) found that algal abundance and nutrient enrichment favour the survival of opportunistic bacteria such as *Pseudomonas aeruginosa* and *Aeromonas hydrophila*, linking eutrophication to increased health risks. Onohuean, Okoh, and Nwodo (2022) reported widespread contamination and antibiotic resistance of *Vibrio* in surface waters of Uganda, consistent with warming-related proliferation observed in the Baltic and Asian seas. These findings support the hypothesis that combined increases in temperature and nutrient loading enhance the persistence and virulence of waterborne pathogens. Several pathogenic microorganisms commonly associated with water pollution include *Staphylococcus aureus*, *Streptococcus pneumoniae*, *Enterococcus* spp., *Salmonella* spp., *Escherichia coli*, *Klebsiella pneumoniae*, and *Clostridium botulinum*, among others. Their persistence in aquatic environments is enhanced by warmer temperatures and nutrient-rich conditions, increasing the risk to human health.

Chemical pollution has been equally serious and often chronic in aquatic ecosystems. Mahabeer and Tekere (2021) found high levels of cadmium and chromium in the South African Umdloti River, attributed to agricultural and industrial wastewater. Potapowicz *et al*. (2022) showed that polycyclic aromatic hydrocarbons found in Antarctic waters are derived from atmospheric deposition; thus, long-range transport leads to the spreading of contaminants far beyond their emission source. In Europe, Wang *et al*. (2021) proposed an integrated framework for the relationship between sediment pollution and ecosystem-service loss and estimated economic losses of up to USD9000$\cdot$ha$^{-1}\cdot$y^{-1} in Dutch and Flemish rivers. The results highlight that chemical pollution does not respect city boundaries and is a widespread transboundary problem that requires concerted monitoring and policy implementation.

Cyanobacterial blooms are another major threat to water quality, strongly influenced by climate. Jin *et al*. (2022) proposed an iron-based pre-oxide/combined coagulation method for removing *Microcystis aeruginosa* and alleviating membrane fouling in treatment plants. Ren *et al*. (2021) showed that the abundance of benthic cyanobacteria in Lake Chaohu, China, fluctuates seasonally with temperature and sediment dynamics, and Lu *et al*. (2021) linked emerging pollutants, such as microplastics and ionic liquids, with cyanobacterial stress responses. Taken together, these results highlight a close relationship among algal bloom occurrences, warming, and nutrient inputs, and thus emphasise the importance of nutrient load management and the implementation of advanced treatment processes. Overall, the ramifications of climate change make existing trajectories of water pollution worse through extreme rainfall, warmer waters, and disrupted biogeochemical cycles. Consequently, subsequent microbial, chemical, and ecological pressures pose major threats to human health, biodiversity, and ecosystem services. Regardless of technological advances – from sophisticated pathogen detection to hybrid coagulation systems and bioindicator surveillance – the global implementation of these technologies still faces major challenges. Addressing these challenges requires institutionalising tighter effluent standards, deepening international cooperation, and applying adaptive management frameworks that link climate policy to water-quality governance, ultimately promoting resilient and sustainable freshwater systems.

WATER-RELATED DISASTERS AND RISK MANAGEMENT

Climate change is increasing the frequency and severity of hydrological hazards (floods, droughts, wildfires, and cyclones), with severe environmental and socio-economic impacts. The risks result from complex interactions among oceanic, atmospheric, and terrestrial systems, and their effects are further amplified by urbanisation, ecological degradation, and the lack of risk management systems.

Flooding remains the most common hazard worldwide. Silva da, Alencar and Almeida de (2022) presented a Non-Stationary Multi-Attribute Utility Theory (NSMAUT) framework for evaluating urban flood risks under a range of demographic and climatic scenarios, and showed that adaptive and time-dependent evaluations significantly enhance decision-making for flood protection. Janizadeh *et al*. (2021) used machine learning ensemble techniques to predict flood susceptibility in the Kalvan watershed in Iran under the representative concentration pathway (RCP) 2.6 and RCP 8.5 scenarios; their model showed that land use change and extreme precipitation are the major factors that amplify flood risk. Li *et al*. (2020) showed that almost 40% of the world's regions have become more vulnerable to flooding since 1985, and this is attributed to the interaction of anthropogenic and climatic drivers. Hochrainer-Stigler *et al*. (2020) proposed a quantitative resilience rating system that relates community preparedness to infrastructure design, which is a practical tool for improving local response capacity. Socio-economic impacts are acute: in Bangladesh's Char Village, Hossain, Sohel, and Ryakitimbo (2020) found that two-thirds of household income was lost post major floods, which resulted in asset disposals and migration – an empirical example of the urgent need for targeted recovery initiatives.

Drought is another form of climatic extremes that causes crop failure, groundwater depletion, and loss of livelihood. Cacciotti *et al*. (2021) showed through the ProteCHt2save project that the combination of information and communication technology (ICT)-based geographic information system (GIS) platforms with decision-support tools strengthens regional drought risk management. Ulibarri and Scott (2019), analysing the 2012–2016 drought in California show that the prolonged crisis triggers institutional change but also reveals weaknesses in long-term climate adaptation in infrastructure licensing. Nepal, Tripathi, and Adhikari (2021) found that drought and soil erosion are the main drivers of seasonal migration in semi-arid areas, while Zhang *et al.* (2021) quantified drought sensitivity of winter wheat in northern China and attributed yield loss to a reduction in precipitation and heat stress. Collectively, these studies highlight the value of adaptive farming practices and improved soil moisture management.

Wildfires are becoming increasingly common along with drought and heat extremes. Mansoor *et al.* (2022) identified that the frequency of forest fires in the world has increased significantly since 1984 due to changes in the physiology of the vegetation and fuel moisture. They recommended measures in sustainable forest management, such as stress-predictor assessment, community education, and the utilisation of indigenous species to combat fire susceptibility. Parente *et al.* (2018) projected that under RCP 8.5, southern Europe will face unprecedented heat wave intensity and wildfire incidence, requiring more robust investments in adaptation. Mishra, Alnahit, and Campbell (2021) further linked wildfire events to post-fire declines in water quality, highlighting the need to consider watershed restoration alongside fire management strategies.

Cyclones are another major hydro-meteorological threat. Rehman *et al.* (2021) examined coastal communities in Bangladesh and found that informal social networks and local institutions play a decisive role in recovery and adaptation after storm surges. Mohapatra, Harish and Dwivedi (2021) showed the need for cyclone-resilient housing and early warning infrastructure in rural areas, and Zhou and Zhang (2021) reported severe tropical cyclones in Hong Kong, leading to long-term economic disruptions despite stable gross domestic product (GDP) growth, demonstrating the hidden costs of recovery.

In aggregate, evidence from across these hazard types shows that climate change increases hydrological extremes and reveals inadequacies in preparedness. Although predictive models and resilience frameworks have made progress, more needs to be done on multi-hazard mapping, early warning systems, and community-based adaptation. Strengthening interdisciplinary research and incorporating geospatial data with socio-economic data into planning processes will be key to minimising losses and supporting long-term resilience in vulnerable areas.

AGRICULTURAL AND SOCIO-ECONOMIC IMPACTS

Climate change has profound impacts on agriculture and fisheries, threatening food security and rural livelihoods through changing rainfall patterns, rising temperatures, and more frequent extreme events. Crop systems are especially sensitive to changes in precipitation and temperature, which influence planting time, pest incidence, and soil-water balance. Sitko, Scognamillo and Malevolti (2021) studied smallholder adaptation in Ethiopia and Malawi and found that food aid programmes helped poor households to adopt expensive climate adaptation practices (CAPs) such as conservation tillage and improved water management. These measures increased resilience against drought but also indicated the financial barriers to widespread adoption. Similarly, Ruppel (2022) noted that global trade policies under the World Trade Organization indirectly impact sustainable agriculture by regulating soil conservation and biodiversity conservation through market incentives.

Model-based analyses are also used to illustrate the complexity of interactions between climate and agriculture. Kang *et al.* (2022) used the soil and water assessment tool (SWAT) model with representative concentration pathway (RCP) 2.6, RCP 4.5, and RCP 8.5 scenarios to simulate the yield of crops at the watershed level. The results showed a consistent decrease in potato and barley yields across all scenarios, with a severe yield reduction under RCP 8.5 due to heat-stress-induced soil moisture losses. In the study by Aurbacher *et al.* (2013), for Europe's cereal systems, the FARMACTOR and EXPERT-N models were used to investigate shifts in sowing and harvesting seasons, increased yield fluctuations, and a long-term decrease in output without technological innovation. Derbile, Bonye and Yiridomoh (2022) identified drought as the most devastating hazard of staple crops like maize and rice in West Africa, and recommended the deployment of climate smart agriculture (CSA) techniques, including intercropping, drought-tolerant varieties, and supplementary irrigation to maintain production. In Italy, Farina *et al.* (2011) showed, using the environmental policy integrated climate (EPIC) model, that no-till practices result in less soil erosion and greater carbon sequestration. However, yield improvements depend on crop rotation patterns. Together, these studies reinforce the importance of CSA and better land-use modelling for adapting cropping systems to future climate conditions.

The aquatic and fisheries sectors are also at great risk (Daly *et al.*, 2021), as demonstrated by the analysis of Canada's 2021 maritime strategy, which highlighted that integrating climate research and community monitoring strengthened adaptive capacity among coastal fisheries. In South America, Peluso *et al.* (2022) predicted an 85% reduction in native fish species in the Upper Paraguay River Basin due to the cumulative effects of warming and dam construction, which disrupt migratory habitats. From the study presented (Robinson *et al.*, 2022), the authors reported that coral-reef fisheries continue to be important for the micronutrient supply and are highly susceptible to bleaching events. Gianelli *et al.* (2021) documented that toxic algal blooms severely impacted small-scale clam fisheries in the South Atlantic in terms of revenue. However, short-term adaptive responses, such as diversification and early-warning systems, helped offset the impact. Similarly, Song *et al.* (2022) emphasised that genetic improvement and diversification of aquaculture species can enhance protein supply and economic resilience, and offer pathways for sustainable growth in the face of climate stress.

The socio-economic implications of such agricultural and aquatic disruptions are significant. Changing yields and diminishing water availability make incomes increasingly precarious and make agricultural populations in agrarian economies more vulnerable to poverty. Ausseil *et al.* (2019) modelled global climate-economic interactions and showed that regional adaptation policies may buffer productivity losses while retaining ecosystem services. Reidsma *et al.* (2015) confirmed, through bio-economic simulations in the Netherlands, that an integrated approach combining farm and landscape levels of adaptation is superior in terms of economic and environmental outcomes compared with isolated interventions. Moreover, Hălbac-Cotoară-Zamfir, Keesstra and Kalantari (2019) demonstrated the role of nature-based solutions in Romania in countering land degradation and enhancing socio-economic resilience, demonstrating the capacity of green infrastructure to deliver ecological and financial co-benefits.

Overall, the body of evidence suggests that climate change impacts across agriculture and fisheries have direct socio-economic destabilising effects through food insecurity, job losses, and supply chain disruptions. Integrating CAPs, CSA, and sustainable aquaculture practices, along with targeted financial support and regional adaptation frameworks, is critical to developing climate-resilient food systems. Future policies should emphasise cross-sectoral approaches linking agriculture, water management, and trade to ensure equitable and sustainable livelihoods under changing climate conditions.

WATER GOVERNANCE AND SUSTAINABILITY STRATEGIES – EQUITY AND INCLUSIVE APPROACHES IN WATER ALLOCATION

Water sharing is an essential component of sustainable water management and enables fair access for all users, as shown in Table 1. Valipour *et al.* (2024) state that equity of water-resource allocation must be multi-dimensional, incorporating economic, environmental, and social aspects. Turley (2023) examined urban-rural water allocation and suggested that urban utilities tend to capture water at the expense of rural users, highlighting the need to assess the equity implications of reservoir reoperation. Wegerich (2007) noted the complexity of achieving equity in transboundary basins like the Amu Darya, where equity is difficult to define and implement. Williams *et al.* (2023) highlighted the critical importance of diversity and inclusion within governance structures to ensure fair representation. Furthermore, Li (2023) demonstrated that intelligent algorithms can be used for water distribution optimisation, which is beneficial for protecting ecosystems and maintaining social stability.

Table 1. Summary of key studies on equity, inclusive governance, and technological solutions for fair water allocation

Focus	Key insights	Reference
Equity and justice in water allocation	advocates for a balance of economic, environmental, and social dimensions in water governance	Valipour *et al.* (2024)
Urban vs rural water allocation	examines the impact of water reallocations on rural users due to urban demands	Turley (2023)
Transboundary water allocation	highlights challenges in achieving equitable water sharing across international borders	Wegerich (2007)
Inclusive water governance	stresses the importance of diversity, equity, and inclusion in water resource management	Williams *et al.* (2023)
Intelligent algorithms for water distribution	demonstrates how technology can optimise water allocation, balancing equity with environmental goals	Li (2023)

Source: own elaboration based on literature.

CONCLUSIONS

The review provides an extensive analysis of the mechanisms by which climate change affects global water systems, covering hydrological, chemical, biological, and socio-geological dimensions. The findings highlight the interrelatedness of water scarcity, water pollution, and governance, all of which are intensified by changing climatic conditions. A good working knowledge of these dynamics is critical to formulating adaptive, equitable, and sustainable management strategies. The main conclusions are detailed below.

1. Anthropogenic climate change alters precipitation, evapotranspiration, and snowmelt regimes, thus leading to reductions in river discharge and decreases in groundwater recharge and increasing water stress in different climatic zones.
2. Elevated temperatures linked to increases in precipitation events result in increased nutrient loading, additional microbial contamination, and heavy metal accumulation, which can increase aquatic ecosystem risks and public health implications.
3. Floods, droughts, wildfires, and cyclones have become more frequent and severe. They are causing socio-economic losses, underscoring the urgent need for early warning systems and integrated disaster risk management.
4. Changing rainfall and temperature regimes compromise the yields of crops, fisheries productivity, and rural income stability, while equitable water distribution and nature-based solutions increase resilience.
5. Future studies are recommended to focus on combining advanced hydrological models with socio-economic datasets, the use of artificial intelligence-based predictive tools, and enhancing transboundary cooperation for achieving adaptive, inclusive, and sustainable water governance.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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