Chapter

Impact of Climate Change on Surface Water Resources

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Abstract

Water is essential for life and is a key in regulating the global climate by transferring heat. However, climate change significantly threatens surface water resource availability, quality, and distribution due to rising temperatures, altered precipitation patterns, rising sea levels, and extreme weather events disrupting hydrological cycles. Climate models project that the Earth's global average temperature would increase by an extra 4°C in the twenty-first century if greenhouse gas concentrations persist. The global average precipitation may rise by 7% for each degree of temperature increase, indicating a future characterized by increased rainfall and snowfall and a higher risk of flooding in certain areas. The planet has surpassed the 1.5°C threshold for global temperature increase, causing thermal stratification in water bodies, reducing oxygen levels, and harming aquatic life. Additionally, rising sea levels contribute to the salinization of coastal freshwater resources. For instance, by the 2050s, a 20–30% reduction in renewable water resources is projected in numerous semi-arid and arid regions due to climate change, with water scarcity intensifying, potentially costing certain areas up to 6% of their GDP. Conservation strategies such as integrated water resource management (IWRM) and wetland restoration are essential to mitigate these impacts and ensure the sustainability of water resources.

Keywords: climate change, surface water resources, hydrological cycles, water scarcity, aquatic ecosystems, conservation strategies

1. Introduction

Water is an essential natural resource [1]. All living things require water to survive, with 71% of the earth's surface water and 29% land. Of the total available water, 97% is saline (sea and oceans), and hardly, 3% is freshwater (lakes, rivers, streams, frozen icecaps, glaciers, snow, and underground water) [1, 2]. Water is found in three states, namely solid, liquid, and gas, which makes the Earth suitable for the existence of life on it. It also modifies the climate through energy redistribution during the transformation of different phases [2]. Lakes and reservoirs serve as long-term storage systems, while rivers and streams provide connectivity and water transport across landscapes [3]. Wetlands, often called nature's kidneys, filter and purify water, and streams are vital for groundwater recharge and habitat support [4].

Water is crucial in transferring energy globally, moving heat from the tropical regions toward the poles. Without water, the Tropics would become increasingly hotter, while the Polar Regions would grow colder. However, the presence of water helps regulate these temperature differences, preventing extreme climate conditions in these regions. The importance of surface water resources extends beyond their ecological roles. These systems underpin human livelihoods by providing drinking water, irrigation for agriculture, and energy production through hydropower. Agriculture utilizes around 70% of freshwater, predominantly for irrigation on a global basis (FAO, 2020). Additionally, surface water sustains diverse ecosystems, supporting biodiversity hotspots and serving as critical habitats for aquatic and terrestrial species [5]. Wetlands offer numerous cultural, supporting, regulating, and provisioning ecosystem services [6].

At present, surface water resources are jeopardized by a changing climate, manifested by alterations in precipitation patterns, increased temperatures, and extreme weather phenomena, which impact hydrological cycles, quality, distribution, and water availability [7, 8]. The Intergovernmental Panel on Climate Change (IPCC) reports that warming has already led to decreased snowpacks and glacial retreats, which feed major river systems, and increased evaporation rates, further reducing freshwater supplies [9]. Surface water systems exhibit significant risk due to rainfall timing and intensity changes, progressively leading to droughts and flooding based on geographic regions. These disruptions threaten aquatic ecosystems and have far-reaching implications for human water security, agriculture, and energy production. Consequently, researchers must realize the dynamics of surface water systems and the impact of climate change on their functionality to address these issues. Sustainable management practices and adaptive strategies are critical for mitigating the effects of a changing climate on these vital resources.

2. Factors influencing surface water dynamics

Climate change drives several significant changes in environmental conditions that directly affect surface water resources, including increased temperatures, altered precipitation patterns, and rising sea levels. These drivers influence water availability, quality, and ecosystem health, posing severe challenges to managing surface water systems.

2.1 Increased temperature

The rising global temperature due to climate change would accelerate evaporation rates, reducing the surface water availability of rivers, lakes, and reservoirs. The planet has surpassed the pre-industrial threshold limit of 1.5°C for global temperature based on the European Copernicus Climate Service, despite the efforts of world leaders a decade ago to prevent exceeding this limit. This phenomenon disproportionately affects arid and semi-arid regions, where water loss due to evaporation exceeds annual precipitation [10]. Prolonged periods of elevated temperatures also contribute to increased thermal stratification in lakes and reservoirs, which reduce oxygen levels and negatively affect aquatic life [11, 12].

Additionally, the loss of snowpacks and glacial meltwater, primary sources of seasonal flows for many rivers, further exacerbates water scarcity. Glaciers and snowpacks store water during the colder months and release it in the warmer seasons [13].

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However, studies indicate that many glaciers globally retreat due to rising temperatures, threatening water supplies for downstream communities and ecosystems [14]. The reduction in snow cover and land ice extent correlates positively with increasing land surface temperatures [15]. Satellite data indicate a probable decrease of approximately 10% in snow cover extent since the late 1960s [16]. The Himalayan region, for example, has experienced significant glacial loss, reducing the flow of major rivers like the Ganges, Indus, and Brahmaputra [17].

2.2 Changes in precipitation patterns

The spatial distribution of precipitation, intensity, and timing will shift due to climate change [16]. Some regions experience shifts in rainfall seasons, leading to unpredictable water availability, while others experience changes in the duration and intensity of rainfall events. For instance, there has been an observed decline in rainfall in Australia [18], China, and the small Island States in the Pacific, increased precipitation variability in the equatorial areas, and increased precipitation in the Northern Hemisphere [16]. Besides, the magnitude and frequency of precipitation events have intensified worldwide, leading to flash floods and overflows in rivers and reservoirs [9]. Conversely, reduced rainfall in drought-prone areas intensifies water scarcity, drying up rivers and lakes [19].

Prolonged droughts and severe floods are becoming more frequent [20]. Droughts reduce surface water levels and disrupt the hydrological cycle, while floods overwhelm existing water infrastructure, causing sedimentation and contamination of water bodies [21]. For instance, severe South Asian flooding during monsoons [22] and droughts in sub-Saharan Africa highlight how precipitation variability affects surface water systems [23, 24].

2.3 Sea level rise

Global warming threatens coastal freshwater resources through salinization due to rising sea levels [25]. Coastal rivers, estuaries, and aquifers are increasingly at risk of saltwater intrusion as higher sea levels push saline water into freshwater systems [26]. This phenomenon reduces the usability of these resources for drinking water, agriculture, and ecosystem support [27]. Coastal areas are highly vulnerable as they depend heavily on estuaries and river deltas for freshwater [28]. In regions like the Ganges-Brahmaputra Delta and Mekong Delta, salinity intrusion due to rising sea levels has already affected freshwater ecosystems and agricultural productivity [29]. The loss of freshwater in these areas compounds the impacts of reduced rainfall and increased temperatures, creating severe challenges for water resource management [30].

3. Climate change effects on surface water resources

3.1 Hydrological impacts

Climate change significantly affects surface water resources, modifying their hydrological properties, deteriorating water quality, and disturbing ecological interactions [31]. These alterations are interrelated and have extensive implications for human and environmental systems [32]. The hydrological regimes of rivers, lakes, reservoirs, and wetlands are experiencing significant disruptions because of a changing climate [33, 34]. Altered river flow patterns, such as changes in seasonal flow timing and reduced base flows, are among the most notable effects [35]. In snow-fed rivers, earlier snowmelt caused by rising temperatures results in higher spring flows but diminished summer and autumn flows, creating water shortages during critical periods [36]. Similarly, reduced glacier contributions exacerbate low-flow conditions in mountainous regions, where rivers rely heavily on glacial meltwater [14].

Lakes and reservoirs face declining water levels due to increased evaporation and reduced inflows. For example, Lake Mead and Lake Powell in the United States have reached historically low levels, reflecting a broader trend of declining freshwater storage in reservoirs globally [37]. Wetlands and floodplains are also affected by the disruption of natural flood cycles, which play a vital role in nutrient deposition, recharge of groundwater, and habitat creation. Reduced flooding in these areas diminishes their ecological and hydrological functions, jeopardizing biodiversity and water availability [4].

3.2 Water quality degradation

Rising temperatures contribute to the water quality degradation in surface water systems. Thermal pollution from increased water temperatures reduces dissolved oxygen levels, stressing aquatic organisms and creating unfavorable conditions for fish and other species [2, 38]. Lower water levels in rivers, lakes, and reservoirs further exacerbate this issue by concentrating pollutants, including agricultural runoff, industrial waste, and heavy metals, leading to higher toxicity [39].

Eutrophication risks are also rising due to increased temperatures and nutrient inflows. Warmer water accelerates algal blooms, which depletes oxygen levels and produces harmful toxins, threatening aquatic ecosystems and water supplies [40]. These conditions are particularly prevalent in nutrient-rich lakes and reservoirs, where excess nitrogen and phosphorus from agricultural runoff combine with warming temperatures to create "dead zones" devoid of oxygen [2].

3.3 Ecological impacts

The stress caused by hydrological and water quality changes profoundly affects aquatic ecosystems and biodiversity. Changes in flow regimes and water levels reduce the quality of habitats for fish, amphibians, and invertebrates. Species that rely on specific seasonal flows or temperature conditions for spawning or migration, such as salmon and trout, are particularly vulnerable [41]. Habitat loss due to shrinking wetlands and reduced connectivity between rivers and floodplains disrupts critical breeding and feeding grounds for numerous species. These disruptions lead to changes in population dynamics, migration patterns, and species distributions, further threatening biodiversity [42].

Additionally, altered food webs and nutrient cycling result from shifts in primary production and decomposition processes. For instance, increased algal blooms can change the structure of aquatic food webs, favoring particular species over others and reducing ecosystem stability [43]. These cascading effects highlight the vulnerability of marine ecosystems to the integrated pressures of human activities and a changing climate.

Figure 1 depicts the effects of climate change on surface water resources and aquatic ecosystems. It comprises three primary sections: climate change determinants, hydrological cycle consequences, and marine organisms' repercussions. The left panel

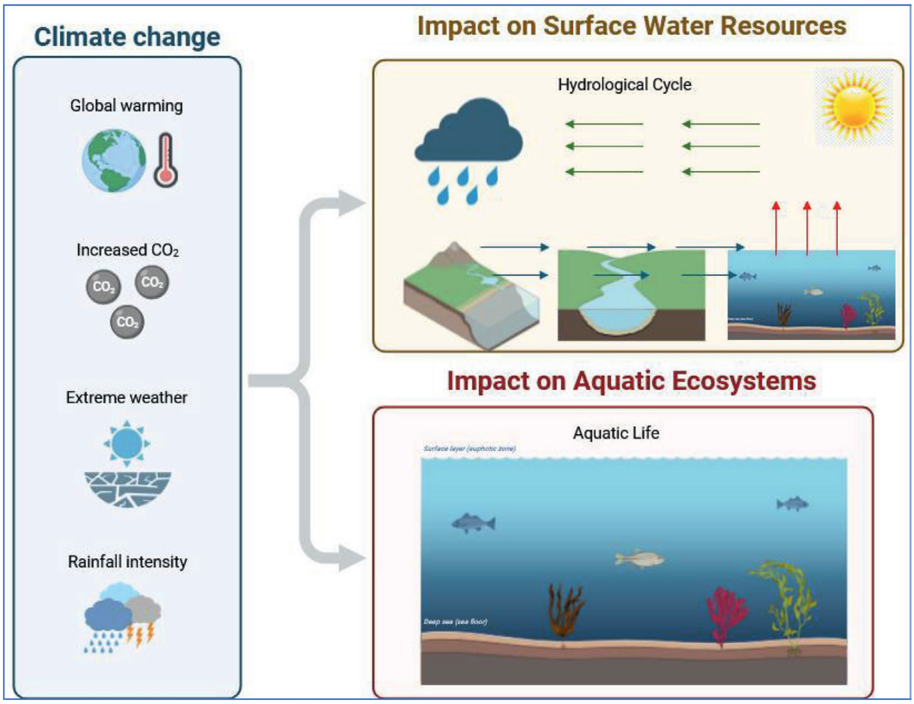

Figure 1.
Impacts of climate change on surface water resources and aquatic ecosystems.

emphasizes the principal causes of climate change, such as global warming, elevated atmospheric CO_2 levels, extreme weather phenomena, and variations in rainfall intensity. These factors collectively affect water supply, quality, and ecological stability.

The upper right panel emphasizes the effects on surface water resources, specifically the hydrological cycle. Elevated temperatures enhance evaporation rates, modifying precipitation patterns and impacting water supply. Severe weather phenomena, including intense precipitation and extended droughts, can result in flooding, alterations in river flow, and water shortages. Moreover, elevated surface water temperatures can diminish water quality by decreasing oxygen levels, resulting in detrimental algal blooms and rendering circumstances less favorable for aquatic organisms.

The bottom right panel underscores the effects on aquatic ecosystems, accentuating disturbances to marine organisms. Elevated water temperatures and oxygen scarcity jeopardize fish populations and other aquatic creatures, compelling them to relocate or confront habitat loss. The diagram differentiates between the euphotic zone, where sunlight penetrates, and the abyssal zone, depicting how climate-induced alterations can disturb marine food webs. Elevated carbon dioxide concentrations also lead to ocean acidification, impacting coral reefs and aquatic biodiversity.

4. Geographical differences in surface water availability

Surface water resource impacts of climate change are not uniform globally [44]. They vary significantly depending on regional climate conditions, geography, and existing vulnerabilities. These variations are most evident in arid and semi-arid regions, polar and mountainous areas, coastal zones, and tropical regions, each facing distinct challenges related to hydrological and ecological changes driven by global warming.

4.1 Arid and semi-arid regions

Arid and semi-arid areas are significantly affected by climate change, as they already experience limited water resources. Climate change exacerbates water scarcity in these regions, leading to more frequent and prolonged droughts. In such areas, the reduced availability of surface water due to increased evaporation and decreased precipitation has significant implications for agriculture, water supply, and ecosystems. For instance, the Sahel region in Africa, traditionally subject to low and variable rainfall, has seen an increase in the severity and magnitude of droughts in recent decades, negatively impacting water resources [45]. Similarly, parts of Australia and the southwestern United States have also reported increased drought conditions, further straining the already limited water supplies for agriculture, industry, and urban use [46].

These regions are also prone to desertification, as higher temperatures and reduced rainfall lead to land and water resource degradation. In response, water management strategies in these regions are increasingly focused on adaptive approaches to drought, such as improved irrigation techniques, water conservation, and desalination [47].

4.2 Polar and mountainous regions

Polar and mountainous regions are experiencing rapid warming, with temperature increases occurring roughly twice the global average in some areas [9]. This warming has profound consequences for surface water resources in these regions, primarily through the accelerated melting of glaciers and snowpacks that provide seasonal flow to rivers. For example, glaciers in the Himalayas, Andes, and Alps are retreating at alarming rates, reducing their contribution to river systems that depend on meltwater for much of the year [14]. In the Arctic, permafrost thawing also affects groundwater flow and increases the release of methane, a potent greenhouse gas [48]. As glaciers shrink, the initial increase in river flow due to more meltwater may be followed by a significant reduction in flow as glaciers disappear, threatening water supplies downstream. Glacier shrinking also reduces freshwater storage, exacerbating water shortages in the long term [36].

4.3 Coastal regions

Coastal regions are affected by a changing climate, mainly through rising sea levels, which leads to freshwater salinization and causes saltwater to intrude into freshwater aquifers, rivers, and estuaries. This is particularly problematic in densely populated coastal areas that rely on freshwater from rivers and groundwater. For example, the Mekong Delta in Southeast Asia is already experiencing significant salinization, affecting agriculture, drinking water, and biodiversity. As seawater encroaches into rivers and groundwater systems, freshwater quality becomes compromised, leading to significant challenges for water resource management [29]. Similarly, saltwater intrusion threatens freshwater supplies in the southeastern

United States, such as Florida, where the population heavily depends on underground aquifers [49].

4.4 Tropical regions

Tropical regions are experiencing increased severity and magnitude of extreme weather events, such as intense monsoons, cyclones, and flooding, exacerbated by climate change. In areas like South Asia and Southeast Asia, the onset of the monsoon season has become more erratic, increasing the severity and magnitude of precipitation. These changes lead to more severe flooding and prolonged dry periods, disrupting water availability and floodplain ecosystems [50].

In the USA, for instance, combining more intense rainfall and extended dry spells in the summer has led to more frequent and damaging floods and droughts [51, 52]. Similarly, in Central America and the Caribbean, increased rainfall and cyclonic activity contribute to more frequent and damaging floods, which overwhelm drainage systems and affect water quality [52]. These disruptions affect water availability and compromise the infrastructure used to manage surface water resources.

4.5 Socioeconomic impacts

Climate change impacts on surface water resources extend beyond environmental degradation to profound socioeconomic consequences [53]. These effects are felt across various sectors, including water supply [54], agriculture [55], energy production [56], and human health. Water scarcity is one of climate change's most significant socioeconomic challenges [57]. As surface water resources decrease in response to rising temperatures, altered precipitation patterns, and increased evaporation, access to safe drinking water becomes more limited [58]. Freshwater availability is already under stress in many regions, particularly in arid and semi-arid zones, and climate change exacerbates these pressures [59]. For instance, in areas like North Africa and the Middle East, water scarcity is compounded by rising temperatures and decreasing precipitation, leaving millions vulnerable to water shortages [60]. In addition to the drinking water supply, industries that rely heavily on surface water, such as manufacturing, cooling processes in power plants, and mining, face increasing operational risks [61]. Reduced water availability can disrupt production processes and escalate operational costs, creating ripple effects throughout the economy [62]. For agriculture, water scarcity diminishes the ability to irrigate crops, leading to decreased agricultural productivity, higher food prices, and food insecurity [63].

Agriculture is significantly affected due to changes in surface water availability, given the sector's heavy dependence on water for irrigation [64]. In many regions, irrigation systems rely on surface water from rivers, lakes, and reservoirs to meet crop demands, especially during dry periods [65]. However, climate change-induced variations in precipitation patterns and the growing frequency of droughts threaten the reliability of these water sources [66]. Irrigation water is essential for sustaining crop yields in South Asia and sub-Saharan Africa, but declining reservoir levels and river flows pose a significant challenge [67]. For instance, the Indus River in South Asia, which serves as a primary irrigation source for millions of people, faces declining flows, jeopardizing food security [68]. As surface water availability declines, farmers may face increased competition for water, leading to conflicts and potential losses in agricultural productivity, particularly for water-intensive crops like rice and cotton [69].

Hydropower is a significant renewable energy source globally, with many countries relying on surface water for energy generation [70]. However, the sensitivity of hydropower production to changes in water flow because of a changing climate presents serious risks to energy security [71]. Reduced river flows and lower water levels in reservoirs limit the capacity of hydropower plants to generate electricity, particularly during dry periods [72].

Climate change affects human health through direct and indirect impacts of surface water resource changes [73]. As water temperatures rise and water availability declines, the incidence of waterborne diseases is expected to increase. Warmer water temperatures promote the growth of pathogens such as cholera, which thrive in warmer environments and increase the risk of contamination in water supplies [74]. In Southeast Asia and sub-Saharan Africa, where clean water availability is already limited, the public health burden of waterborne diseases will likely worsen [75].

5. Strategies for surface water management and restoration

Integrated Water Resources Management (IWRM) is a holistic technique that fosters the harmonized management of land, water, and related resources to enhance social and economic well-being while safeguarding ecosystem health. It emphasizes stakeholder involvement, equitable water distribution, and balancing environmental and human needs. IWRM also integrates surface and groundwater management, recognizing their interconnected nature [76].

Wetlands and riparian zones are critical for water filtration, biodiversity support, and flood regulation. Restoration efforts focus on re-establishing native vegetation, reconnecting floodplains, and enhancing natural hydrological processes. These measures improve water quality, stabilize riverbanks, and provide habitats for diverse species [77]. Wetland restoration also contributes to carbon sequestration, helping mitigate climate change.

Governments and international organizations have implemented various policies to address water ecosystem challenges. Laws like the Clean Water Act in the United States and the European Union's Water Framework Directive set standards for water quality and promote sustainable water use. These policies often require regular monitoring, pollution control measures, and habitat protection. Additionally, community-based initiatives and incentives for sustainable practices encourage broader participation in conservation efforts.

6. Summary and future directions

Climate change significantly impacts surface water resources, altering availability, quality, and distribution. Rising temperatures accelerate evaporation and disrupt seasonal water flows, particularly in arid and semi-arid regions. Changes in precipitation intensify floods and droughts, while rising sea levels contribute to saltwater intrusion in coastal freshwater systems. These hydrological shifts threaten biodiversity, water security, and economic activities dependent on stable water access, such as agriculture and hydropower. The socioeconomic consequences are profound, leading to increased resource competition, food insecurity, and disruptions in human livelihoods.

To address these challenges, sustainable water management strategies must be prioritized. Enhancing water conservation, implementing integrated water resource management, and developing climate-resilient infrastructure can improve adaptability. Protecting and restoring ecosystems, reducing greenhouse gas emissions, and strengthening water governance are also essential for long-term sustainability. Advancing scientific research and monitoring hydrological changes will support informed decision-making. By integrating these approaches, societies can mitigate the adverse effects of climate change on surface water, ensuring resilience for both human and ecological systems.

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