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Climate Change and Water Resource Degradation: Understanding Relationships

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Abstract

Climate change significantly degrades global water resources by altering their hydrological characteristics. The greenhouse gas (GHG) effect intensifies extreme weather events like flooding and drought, driven by excessive precipitation and rising temperatures. These events degrade water quality and quantity in reservoirs. Prolonged droughts reduce streamflow, lower groundwater levels, and increase surface water pollution. For example, the Colorado River's streamflow has decreased by 19% since 2000, and Lake Kasumigaura in Japan has experienced warming of 1.8˚C to 3.2˚C, accompanied by increased ammonia (NH_3) and phosphate (PO_4^{3-}) fluxes. Rising temperatures exceeding the critical 1.5˚C threshold amplify water stress, leading to food insecurity, heat stress, water conflicts, and habitat destruction. Conversely, heavy rainfall increases runoff, sedimentation, and the deposition of pathogens and nutrients like phosphorus into aquatic ecosystems. For instance, Lake Victoria's water levels rose by 1.21 m in 2020, causing flooding, while the Odaw River experienced sewage-contaminated flooding, leading to microbiological contamination. Thermal stratification in Lake Tanganyika has further reduced oxygen levels. Flooding and drought also transform carbon sinks, such as wetlands, into sources of carbon dioxide (CO_2) and methane (CH_4), intensifying global warming by enhancing organic matter decomposition and destroying carbon stores like vegetation. These changes disrupt the water cycle, reducing access to clean water, impairing groundwater recharge, and threatening aquatic ecosystems. This review investigates the relationship between extreme weather events, such as droughts, wildfires, and flooding, driven by climate change, and their effects on hydrological processes in the atmosphere. We also examine changes in the water cycle, including alterations in evapotranspiration, runoff, infiltration, and precipitation. These changes directly affect water resources by restricting access to safe and clean water, disrupting groundwater recharge, and degrading daily living standards. Mitigating these impacts requires adopting climate-smart technologies, transitioning to renewable energy, conserving ecosystems, and developing climate-resilient infrastructure. These actions conserve water resources, reduce GHG emissions, and improve people's living standards.

Keywords

Aquatic Ecosystems, Drought, Flooding, Water Quality, Water Quantity

1. Introduction

Climate change, the most significant anthropogenic driver of water resource degradation, affects the water cycle and the spatial and temporal dynamics of the water-energy nexus [1]. It influences water quantity, hydrological processes, and the quality of water across various resources. The primary drivers of these changes are rising GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which contribute to global warming, increased evapotranspiration, and the intensification of extreme weather events like flooding and drought [2]. Global CO_2 levels have risen significantly from a pre-industrial average of 280 ppm to approximately 422 ppm, leading to an intensification of the Earth's temperature [3]. These changes have disrupted natural processes in surface water reservoirs, groundwater systems, and the atmosphere, undermining sustainable water availability. This, in turn, affects food security, biodiversity, public health and economic growth [4]. Furthermore, the alterations in climate leading to extreme weather events contribute to the destruction of aquatic ecosystems, degradation of carbon (C) sinks such as wetlands, deterioration of soil, water, and vegetation quality and lead to limited access to safe water by people and livestock [5].

Globally, research indicates that over 3.6 billion people (46%) are facing water scarcity, which has resulted from reduced water levels in reservoirs [6]-[8]. Regions in arid areas such as West Asia, Central Asia, and North Africa have experienced variations in both high and low temperatures, along with generally negative precipitation patterns [9]. Frequent heatwaves in North America and the United States have been linked to deteriorating river water quality, with increased mobilization of nitrogen (N), phosphorus (P), and metals such as iron (Fe) and mercury (Hg) due to thawing arctic permafrost [10].

Africa is a continent highly susceptible to the effects of climate change, primarily due to inadequate infrastructure and limited capacity to adapt to these changes [11] [12]. Key vulnerabilities include insufficient water storage and irrigation systems, weak flood control measures, inadequate early warning and monitoring systems for floods and droughts, fragile energy infrastructure, and poor coastal protection. For instance, waterways such as the River Nile, the Niger, and the Zambezi are used for various human activities like agriculture, industrialization and domestic water use which has resulted in reduced water discharge, groundwater depletion and deterioration of wetlands [13]-[15].

Today, activities like hydropower and irrigation face water stress due to changes in precipitation frequency and increased evapotranspiration in some water bodies, such as River Tana basin in Kenya [16]. In Uganda, rainfall pattern variations have reduced Lake Victoria's water levels and shrunk key wetlands, which were vital water reservoirs [17]. This wetland deterioration continues to lower water quality downstream by reducing natural filtration [18]. Lower water quantity increases pollutant concentration, oxygen demand, salinity, and algae growth. For example, groundwater and surface water in Bangladesh were salinized by rising sea levels, while River Rwizi in Uganda experiences high turbidity and nutrient pollution during extreme rainfall events [19].

The continuous deterioration of global water resources significantly contributes to biodiversity loss, particularly in aquatic ecosystems, due to hypoxic conditions and rising temperatures. This degradation, compounded by insufficient water, is intensified by high water treatment costs driven by pollutant accumulation. Unpredictable rainfall patterns further exacerbate food insecurity, increasing public health risks. This review explores the intricate connections between climate change and water resource degradation, emphasizing their effects on the hydrological cycle, GHG emissions, the C cycle, and water quality and quantity of various water resources around the world. It also draws on existing literature to propose adaptation and mitigation strategies aimed at enhancing global living standards.

2. Overview of the Hydrological Cycle and Its Purpose

The hydrological cycle, also known as the water cycle, refers to the continuous movement of water within the Earth's systems, encompassing interactions between the biosphere, lithosphere, atmosphere, and anthroposphere [20] [21]. Water in the hydrological cycle exists in three states which include liquid, solid and vapor. The hydrological cycle serves as a foundational process for other biogeochemical cycles such as the C and N cycles. The changing climate significantly disrupts hydrological processes in watersheds, leading to water stress within the water cycle [1] [22] [23]. However, there is limited quantification of the rate at which hydrological processes respond to increasing changes in climate. The major drivers of these changes and processes in the hydrological cycle are solar radiation and gravity [24]. It is estimated that the entire Earth uses about 36% of the solar energy to convert water into steam vapor. This solar energy supports the change of state of water through melting, sublimation, evaporation, freezing, condensation and deposition, which are key processes of the hydrological cycle (**Figure 1**).

The hydrological cycle is essential for sustaining life, as it ensures the availability of water for humans, plants, animals and other organisms within their respective ecosystems [12]. It also regulates global weather patterns, including precipitation and temperature dynamics within the Earth's atmosphere. The hydrological cycle maintains the presence of water in various reservoirs such as rivers, lakes, and groundwater aquifers, enabling the continuity of physical, chemical, and biological processes [25]. Recycling water is essential to prevent a shortage of clean water, a vital resource for life. While consumed water returns to the hydrological cycle, its availability for reuse depends on effective recycling practices which can be significantly influenced by changing weather events [26]. Nevertheless, there is an inadequate evaluation of how the efficiency and sustainability of water recycling are being influenced by climate variability regionally and globally.

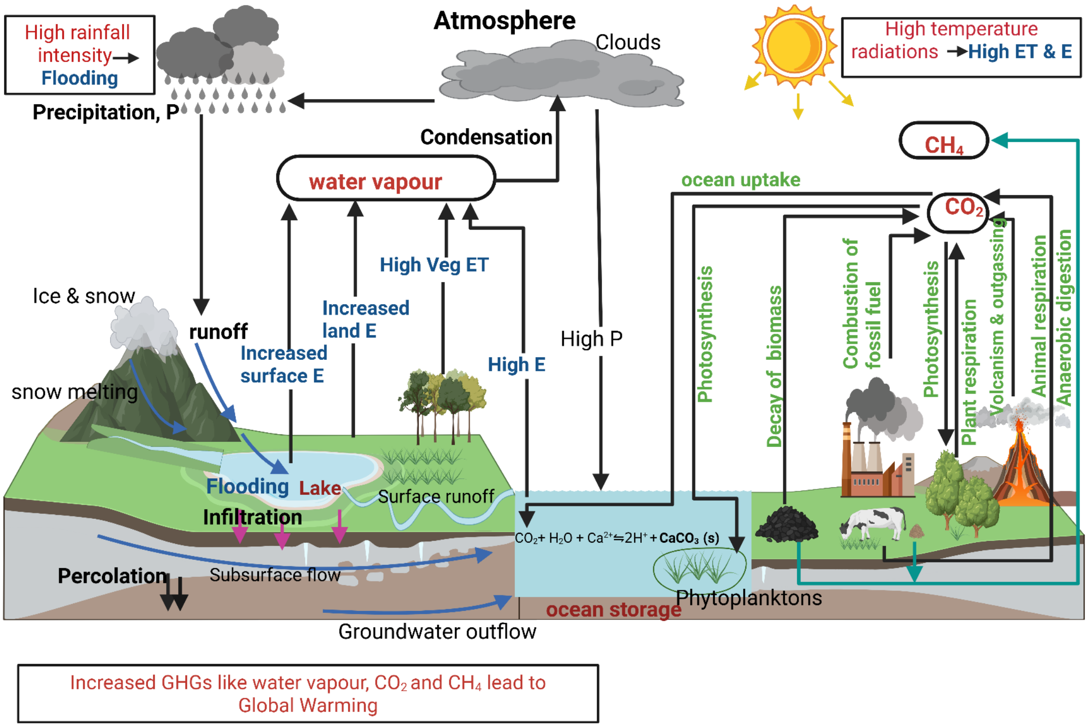

Figure 1. Schematic diagram showing the hydrological cycle and carbon cycle processes (E: Evaporation, P: Precipitation, ET: Evapotranspiration, Veg: Vegetation).

The hydrological cycle comprises several natural processes including precipitation, evaporation, condensation, infiltration, runoff, and transpiration (**Figure 1**). These hydrological processes involve the transfer of the Earth's water from the oceans and other water bodies to the atmosphere (evaporation), facilitated by solar radiation. The water vapor thereafter condenses to form clouds and returns to the Earth's surface as precipitation, which subsequently flows into the ocean, completing the cycle through renewing evaporation [27] (**Figure 1**). In this review, precipitation refers to any form of water released from the atmosphere to the Earth's surface, manifesting as rain, snow, sleet, hail, or freezing rain [28]. Studies indicate that the ocean contributes approximately 85% of global evaporation, with the remaining portion originating from land surfaces. The volume of water evaporated from the ocean annually exceeds the precipitation received in the same period [29] [30].

The main global reservoirs of water include oceans, lakes, aquifers, and the cryosphere such as glaciers and ice sheets. Approximately 1.4 billion cubic meters or 97% of the water in the hydrological cycle, originates from the ocean and a single drop requires thousands of years to reach the atmosphere [31]. Glaciers account for 2.1% of the Earth's water, while groundwater represents 0.6%, with less than 1% distributed as soil moisture and atmospheric water. Glaciers are recognized as the second-largest freshwater reservoir. The ocean receives about 40% of rainfall through river runoff and approximately 20,000 cubic kilometers from groundwater recharge [32].

2.1. Global Implications of Climate Change on the Hydrological Cycle

The major challenges posed by climate change globally include increasing temperatures and altered precipitation patterns [33]. Approximately 4 billion people globally face water scarcity, with regions such as China experiencing reduced water flow, declining water tables, and wetland shrinkage [34]-[36]. Key river basins, including the Yellow River Basin in China, the Murray-Darling Basin in Australia, and the Mekong River Basin in Southeast Asia, are under severe water exploitation, impeding sustainable development [37] [38]. In Africa, countries such as Kenya, Somalia, South Sudan, Tanzania, Burundi, and Uganda experienced severe drought conditions during the periods 2008-2009, 2010-2011, and 2016-2017 [39] [40].

There can be profound impacts of climate change on the water cycle, influencing water and energy balances, hydrothermal coupling, and river discharge across varying temporal and spatial scales. But there is an absence of interactions between water and energy fluxes across scales in the existing hydrological models. Among the key indicators of climate change on water resources are the rising sea levels, glacier melting, freshwater scarcity, and ecological disruptions, which have been extensively documented [41] [42]. The current changes in precipitation intensity and frequency further underscore the changing climate's role in maintaining the current global water-balance [25]. Substantial unpredictability for future precipitation extremes exists especially in areas with limited data.

Changing precipitation patterns are a critical factor considered in this review, as they greatly affect agriculture, which consumes about 70% of global freshwater for irrigation. This makes agriculture highly vulnerable to the ongoing decline in water availability. Furthermore, drought has played a key role in reducing river water levels, leading to the extinction of aquatic, floodplain, and human ecosystems. The disruption of the ecosystem primarily causes the destruction of habitats, including wetlands, rivers and lakes. A study of River Naoli Basin in China focused on assessment of runoff and drought patterns. The authors revealed a significant increase in drought frequency during summer, leading to reduced runoff in waterways. The decline in River Naoli's water levels caused the extinction of some aquatic ecosystems through habitat destruction, leading to biodiversity loss, vegetation stress, and reduced water quality [43]. Such situations require urgent attention to prevent a severe water crisis in the vulnerable regions of the world in the near future.

2.2. Increase in GHG Emissions, Elevated Temperatures, and Changes in Water Distribution

In the past and current centuries, human activities, especially industrialization and burning of fossil fuel, have significantly increased GHG and aerosol emissions [44]-[46]. This has resulted in changing climate patterns that are affecting water resources [2] [47] [48]. However, there is uncertainty in the relative contributions of sources of emissions to the variations in regional hydrology.

Increased Earth's surface temperatures and energy imbalance resulting from amplified GHG effect has strongly contributed to the alteration of the water cycle through thermodynamic and plant physiological processes. In particular, the temperature difference caused by elevated CO_2 levels enhances the rate at which water vapor is trapped in the atmosphere by approximately 7% per ˚C of warming [49]. Rising CO_2 levels induce physiological processes that reduce stomatal conductance and enhance water-use efficiency, thereby decreasing transpiration rates. The suppression of moisture movement can disrupt terrestrial moisture recycling, thereby inhibiting precipitation. Typically, vegetation emits water vapor that condenses to form clouds, which subsequently contribute to local and regional rainfall [49]. On the other hand, the intensity and frequency of precipitation increase due to elevated evapotranspiration rates, particularly in areas with high humidity.

Numerous studies indicate that ongoing anthropogenic activities are expected to exacerbate the impact of climate change on water resources for future generations [12]-[50]. Rising temperatures have reduced water levels and disrupted water distribution and circulation between the Earth's surface, atmosphere, and subsurface, leading to water resource degradation [51]-[53]. Extreme weather conditions like drought events reduce the extent of groundwater recharge in the aquifers. Additionally, rising temperatures accelerate evapotranspiration, reducing groundwater recharge, depleting soil moisture, and decreasing water runoff in rivers and streams. But the extent to which these alterations become irrevocable is yet to be clearly understood. The Colorado River Basin serves as an example of a region significantly impacted by evapotranspiration driven by rising temperatures. Studies indicate that the streamflow of the Colorado River decreases by approximately 9.3% per ˚C of warming [54]. This moisture loss has contributed substantially to the depletion of water resources, posing challenges to water management for the communities in the surrounding areas [55].

Several regions, including those in the tropics, have experienced significant impacts from rising temperatures. The tropics face an increased frequency of extreme rainfall leading to floods and erosion. Subtropical zones are also experiencing heightened heat stress and aridity, which contribute to water conflicts [56].

Temperate regions, on the other hand, are encountering seasonal climatic contrasts characterized by wetter winters and more intense summer heatwaves and droughts [57]. The Intergovernmental Panel on Climate Change (IPCC) has documented global warming effects, with thermometer data from various regions showing average temperatures 1.1˚C to 1.5˚C above pre-industrial levels, surpassing the 1.5˚C threshold in 2024.

3. Impacts of Climate Change on Water Reservoirs

3.1. Changes in Precipitation Patterns and Water Quantity

The spatial and temporal distribution of rainfall has been significantly altered by climate change, leading to variations in water levels across different water bodies [2] [24] [58] [59]. The primary factor that influences water quantity in surface water bodies and groundwater is precipitation. Precipitation intensity and frequency determine the occurrence of major events in some areas, such as excessive rainfall that causes floods or long-term dry periods which indicate drought.

3.1.1. Drought

Drought in this review refers to the reduced frequency of precipitation coupled with increased temperatures for a prolonged period [60]. Most tropical and subtropical regions in the world are facing frequent droughts resulting in decreased streamflow [61]. Changes in precipitation patterns, marked by longer dry periods and shorter wet ones, lead to reduced water discharges. The reduction of water quantity in water reservoirs occurs when rainfall and inflows from snowmelt and groundwater cause depletion of water bodies. Furthermore, reduced groundwater recharge, and continued human water withdrawals for industrial and domestic use during dry spells lead to shrinkage of both surface and subsurface water. This decline in water availability impacts irrigation, agriculture and hydropower generation [62]. Evidence reveals that River Mekong Basin received a record-breaking drought in 2019 with low precipitation from May to October amounting to 71.9% of the climatological mean which contributed to low stream flows [63] [64]. Literature also indicates that since 2000, River Colorado's water flow in the US has reduced by 19% as influenced by the decrease of spring season precipitation (drier springs) that contributed over 80% of the river discharge [65] [66]. Furthermore, there is increased frequency of dry spells in the horn of Africa particularly in River Nile which has experienced a meteorological drought especially in Ethiopia, Sudan and Egypt leading to reduced river flow [67]. Uganda, a country in East Africa, is also facing climate variability with an increase in drought periods correlated to high temperatures affecting the availability of water [68]. Similarly, the Mediterranean basin has undergone periods of reduced winter precipitation caused by the movement of storm tracks towards the poles since 1970. These long dry periods reduce soil moisture, hinder evapotranspiration from land and surface water, lower humidity, and trigger repeated low rainfall events, which decrease water levels in rivers, lakes and wetlands (**Figure 1**). These effects are particularly significant in countries such as Egypt, Morocco, and Sudan, which rely heavily on irrigated agriculture [69]. Several regions, including subtropical areas and districts in Northern Uganda such as Gulu, Kotido and Kitgum, are also experiencing reduced precipitation due to seasonal changes characterized by extended dry periods compared to wet periods [69] [70]. The above literature confirms how increased length of climate-driven droughts play a vital role in the reduction of water quantity in water reservoirs.

3.1.2. Flooding

Flooding, caused by extreme precipitation patterns, is another critical event analyzed in terms of its frequency, intensity and distribution [71]. Occurrence of floods in urban areas usually happens after rains of short duration and high intensity which submerge the drainage systems causing heavy runoff [72]. This event not only damages the infrastructure but also destroys the municipal water supply treatment plant and deteriorates the water quality through the deposition of nutrients in water resources [73] (**Figure 2**). In a study on Hu-Xi watershed on the upper stretch of Lake Taihu China, over 90% of annual runoff of water resources was stimulated by extreme precipitation periods [74]. These changes in precipitation trends affect water levels. Lake Victoria, the second-largest lake in the world, experienced fluctuations in water levels due to high precipitation. The lake's water level rose by 1.21 metres between late 2019 to 2020, impacting over 29,000 people living within 50 kilometers. These floods caused infrastructure destruction and the displacement of residents [75]. The changing climate in some areas is characterized by more intense rainfall, leading to peak river and stream discharges. This results in fluvial, pluvial, coastal, and dam-burst events, causing water overflow on plains and reducing the rate of water infiltration [76] [77].

3.2. Impact of Increased Evaporation Rates on Water Quantity

A rise in temperatures leads to increased evaporation rates, significantly reducing surface water levels in oceans, rivers, lakes and reservoirs. This not only affects water bodies but also soil moisture levels, which in turn impairs water infiltration and percolation, thereby reducing groundwater recharge. A study in Ukraine demonstrated that surface water evaporation substantially decreases the availability of water in rivers and other water resources [78]. Another recent study modeled the evaporation of Lake Turkana using climate change projections and an artificial neural network model, forecasting average evaporation rates of 23.76, 25.68, 18.89, and 18.57 billion m^3 for HADGEM, MPI 4.5, and 8.5 scenarios, respectively. Lake Turkana in Kenya, an endorheic water resource was reported to lose most of its water by evaporation with an evaporation rate approximated at 92 inches (2335 millimeters) annually [79]. These reduced water levels result in alteration of thermal balance in water resources which may lead to the growth of algae and death of aquatic life reducing biodiversity. The increased evaporation rates also minimize the availability of water supply for irrigation, hydropower and industrial use, hence affecting human well-being. The Zambezi River Basin at Kariba Dam highlights the potential impact of climate change on hydropower energy. Rising temperatures in the region have increased evaporation and reduced Zambezi River flows, significantly affecting hydropower production. Projections suggested a 9% decline by 2020, 18% by 2050, and 28% by 2080 of water quantity [80] [81].

3.3. Changes in Groundwater Recharge and Climate Change

Groundwater recharge occurs when water from precipitation and surface water sources, such as wetlands, rivers, and streams, infiltrates into the soil which replenishes both confined and unconfined aquifers. The presence of cracks facilitates rapid water infiltration to the aquifer compared to the slower percolation through the soil. Assessing groundwater recharge rates is crucial for ensuring sustainable water resource availability [82] [83]. Climate variability directly and indirectly affects groundwater recharge, leading to reductions in the water table, recharge rates, and base flow supporting rivers, streams, and other water bodies [82]. A study in Kiryandongo, Uganda, demonstrated that changes in rainfall and temperature significantly influence groundwater recharge [84]. High-intensity rainfall diminishes infiltration effectiveness due to increased surface runoff in lowland areas. Another study in the Usangu catchment, Tanzania, projects shorter rainy periods and a temperature rise of 6 - 2˚C, potentially causing a 7% reduction in water yield and a 26% decline in recharge [85]. Additionally, high temperatures and evaporation degrade soil by reducing porosity and aggregate stability, which decreases infiltration rates, raises runoff coefficients, and ultimately lowers groundwater recharge. There is a recent trend in Africa, which involves constructing groundwater supply systems to address the growing demand for water. These systems aim to support irrigation and supplement insufficient water for crops, leading to increased groundwater extraction and subsequent depletion of groundwater supplies [86] [87].

3.4. Glacier and Snowpack Melt and the Changing Climate

The increase of CO_2 levels in the atmosphere is considered as the main driver of anthropogenic climate change with 2.29 W m^{-2} or 66% of the global-radiative forcing from 1750 through 2023 [88] [89]. This increase in CO_2 levels has caused a global temperature rise of 1.11˚C, resulting in the melting of glaciers and a rise in sea levels. In temperate regions like Himalayas, Tibetan plateau and tropical regions of Rwenzori Mountain in Africa, elevated temperatures have caused glaciers and snowpacks to melt, leading to a temporary increase in river flow from frozen water stores. Consequently, glacial water stores are being depleted at an exponential rate as the ice continues to diminish [90] [91]. In summary, high temperatures lead to snowmelt, which causes rapid runoff, reducing the detention time necessary for water infiltration. This process diminishes groundwater recharge, ultimately decreasing water availability in reservoirs during dry seasons

(**Figure 2**). Today, the Chhota Shigri region in the Indian Himalayas faces a long-term water security threat due to rising temperatures which have altered glacier lengths. Despite this, the region's water resources remain heavily reliant on glacial meltwater [92]. Mount Rwenzori of East Africa is facing a spatial uniform loss of its glacier due to the elevated air temperatures. Mount Rwenzori glacier's area decreased from approximately 6.5 square kilometers in 1900s to approximately 1 square kilometer in 2003 [93] [94]. In the Rwenzori region, particularly in areas like Kasese, annual flooding events have caused deaths and displacement of people [95].

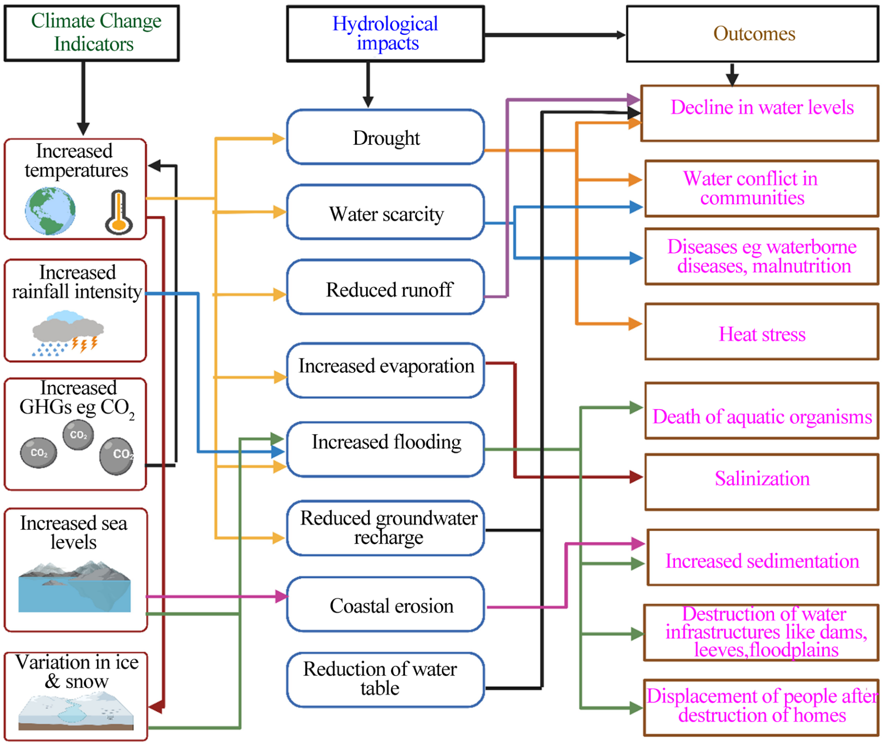

Figure 2. Schematic diagram showing the impacts of climate change on water resources and the ecosystem.

4. Water Quality and the Changing Climate

Extreme hydrological conditions such as floods and drought can increase water quality deterioration. These changes in water quality arise due to variations in frequency and intensity of temperature and precipitation [96]. A study conducted in the Minjiang River Basin in Southwestern China applied a climate water quality (WQ) assessment framework to assess the impact of climate change on water deterioration. The findings indicated that 23% - 35% of the variation in water quality was significant, with precipitation and human activities identified as the primary drivers influencing key water quality parameters [74]. These parameters, including temperature, pH, dissolved oxygen, dissolved organic matter, nutrients, micropollutants, and microorganisms, are critical indicators of water contamination and are closely linked to the occurrence of various diseases [10].

4.1. Impact of Rising Atmospheric Temperatures on Water Quality

Increasing atmospheric temperatures increase water temperatures which greatly affects water quality in several water resources and aquatic biodiversity [97] [98]. Elevated water temperatures reduce dissolved oxygen levels, leading to a phenomenon known as hypoxia. This condition creates a hostile and stressful environment for aquatic organisms, often resulting in their mortality [99]. Rising temperatures contribute to oxygen depletion through increased microbial decomposition of organic matter, particularly by anaerobic bacteria [100]. This process is exacerbated by higher nutrient loads, which, in combination with elevated temperatures, accelerate eutrophication. Eutrophication promotes the growth of algae and cyanobacteria, leading to harmful algal blooms and further oxygen depletion. Warm temperatures enhance these conditions, fostering the proliferation of algae and cyanobacteria. A study conducted in Lake Balaton, Hungary, revealed that increased temperatures stimulated the growth and reproduction of algae and cyanobacteria. This proliferation degraded the water's clarity, taste, and odor [101] [102]. Another study conducted at Dianchi Lake further demonstrated that the temperature of lake surface water significantly influences the occurrence of cyanobacteria blooms [97]. Additionally, warm water may stimulate the release of harmful substances such as NH_3, Hg and other volatile compounds. A study in Lake Kasumigaura, Japan, documented a significant rise in NH_3 and PO_4^{3-} fluxes as water temperatures increased from 1.8˚C to 3.2˚C [103].

4.2. Impact of Changing Precipitation Patterns on Water Quality

Extreme weather conditions such as floods and droughts can influence water quality deterioration [10]. Increased runoff and flooding occur when floodplains are inundated by water from heavier rainfall and more intense storms. In such cases, water sources are often contaminated by sewage, agricultural runoff, and other pollutants, altering the water's physicochemical and biological state and making it unsafe for domestic use. Areas along Odaw River in Ghana have experienced increased precipitation and flooding. These floods resulted in destruction of sewage systems, mixing sewage with surface and groundwater, and caused microbial contamination [104].

The low levels of water flow caused by drought in waterways usually result in stagnation, accumulation of pollutants from agricultural areas, industries and urban areas. Low precipitation also causes salinization which usually affects the taste of water, loss of aquatic habitats, increased turbidity, and increased concentration of heavy metals like iron and manganese [105].

4.3. Impact of Sea-Level Rise on Water Quality

Rising sea levels increases the total volume of ocean water and is considered as one of the most catastrophic outcomes of climate change. These sea levels usually result from melting glaciers and expansion of water caused by increased temperatures. Evidence from satellite data suggested a significant ice melt in Greenland and Antarctica since 1993 with about 270 billion tons melting per year hence causing a substantial contribution to the rising sea level [106]. Research identified that about five sea level rise scenarios are likely to take place in relation to the increasing GHG emissions detected [107]. Scientists also projected that the global sea level rise will increase to 0.28 m by 2050 and more than 1 meter by 2100 [108]. Currently, Mexico is facing a rapid sea level rise with an expected increase ranging from 0.49 to 0.69 m in the next 30 years [109].

During periods of sea level rise, water quality is mainly altered by the flow of salt (sodium chloride, NaCl) water into fresh water sources like rivers, wetlands, and aquifers. This has been reported to affect the coastal ecosystems in major cities like Miami, and Shanghai [110] [111]. When salty water mixes with freshwater due to the rise of sea level, the water chemical composition is altered significantly, rendering it unsuitable for drinking and other domestic uses. Salinization also results in substantial biodiversity loss, including fisheries and river dolphins [112]. Coastal erosion, driven by rising sea levels have been reported to cause sedimentation in waterways, leading to property losses exceeding $500 million in the United States [113]. Rising sea levels displace thousands of people annually, particularly in Pacific Island nations, where over 50,000 individuals migrate yearly. Additionally, the movement of pollutants caused by sea level rise has triggered outbreaks of waterborne diseases where over 70% of the respondents confirmed to be suffering from hypertension, diarrhea, and gastrointestinal issues [114]. The altered water parameters increase the costs of treatment to meet acceptable levels for their intended purposes.

4.4. Impact of Glacial Melt and Snowpack Reduction on Water Quality

Increased temperatures stimulate the melting of glaciers and snowpack which leads to runoff of meltwater to rivers, lakes and increased groundwater recharge [115]. A study of 77 Himalayan glaciers in India revealed shrinkage, snout retreat, thickness changes (−1.27 + 0.37) and mass loss (−1.08 + 0.31) with a reduction of average velocity from 21.3.3 m a^{-1} to 16.68 m a^{-1} by 2020 which showed that glaciers will disappear entirely, having an impact in regional water supply [116]-[118]. During glacial melting, there is a noticed variation in water levels, change in water temperatures, high sedimentation, increased levels of dissolved organic C and release of harmful pollutants in the water. The stored pollutants commonly include mercury, lead and persistent organic compounds which deteriorate water quality. Global history shows that viral diseases such as malaria and Spanish flu have a relationship with glacial melting since viruses are preserved in ice across the Artic and high-altitude tundra [118]. Antarctica and Greenland are known to have ice of 60 m and 7 m respectively which today, is said to melt, resulting in increase in sea levels by 20 cm by the last century [119] [120]. A study in Greenland and Antarctica showed an interrelation between global warming and sea level rise, revealing a 50 m rise for each 2.5˚C [121].

5. Effects of Carbon Cycle Alterations, Sequestration, and Climate Change on Water Resources

The C cycle is the process by which C moves from the atmosphere to the Earth and back to the atmosphere [89]. Carbon is stored in various sinks, including the atmosphere as CO_2, the hydrosphere (oceans), the geosphere (rocks, sediments, and fossil fuels), and the biosphere (plants, animals, and microbes), which release it slowly [21] [122] [123]. Literature reports have shown that one of the most effective C sinks is the Dongting Lake floodplain in China, found to be a continuous and robust CO_2 sink with a flux of -403.7 g Cm^{-2} y^{-1} and the sink mainly depends on the period of inundation and flood water levels [124]. Additionally, the Middle Yangtze River exhibited an annual C budget of -424.3 ± 52.5 g Cm^{-2} [124]. Research also reveals that the carbon sequestration (CS) potential of riverine wetlands, marshy wetlands and lacustrine wetlands have the highest median of CO_2, CH_4, and N_2O flux as 3766.87, 21.36 and 0.33 mgm^{-2} d^{-1} respectively [125]. These C reserves play a crucial role in mitigating GHG emissions [12]. The key processes in the C cycle: photosynthesis, respiration, decomposition, combustion, ocean uptake, weathering and volcanism are all closely linked to climate change and can affect water resources (**Figure 1**).

Research shows that CO_2 concentrations have increased by more than 50% in the atmosphere, since the commencement of industrial practices in the 18th century primarily due to the burning of fossil fuels (coal, oil and gas) and land-use changes [3]. Approximately 151% of the CO_2 level increase since 1750 is attributed to industrial activities. According to the World Meteorological Organization, CO_2 levels exceeded 420 ppm globally in 2023, the highest concentration recorded to date. This rise in CO_2 concentrations has been linked to extreme drought in countries in the African Horn. Furthermore in 2023, other GHGs, including CH_4 and N_2O were measured at 1934 ppb and 336.9 ppb, respectively [126].

Carbon in water is commonly categorized into four different forms which include dissolved inorganic C (CO_2, bicarbonate, and carbonate), dissolved organic C from plants and microbial sources, particulate organic C like plankton and finally gaseous CO_2 and CH_4. Factors that influence CS include hydrology, vegetation type, water table depth, and soil type [127] [128]. The CS as influenced by vegetation mainly depends on the growth rates, biomass production and decomposition rates, soil type which is influenced by water holding capacity and nutrient content. Water table depth commonly influences the availability of oxygen hence resulting in decomposition and C storage [129] [130].

5.1. Wetland Carbon Sequestration in the Changing Climate

Aquatic ecosystems like wetlands act as C sinks through the photosynthesis of vegetation such as mangroves, salt marshes, peatlands, and others. These ecosystems play a vital role in GHG uptake and emission, making them one of the most important ecosystems [131] [132]. Carbon dioxide is commonly stored in anaerobic and water-logged sediments. Wetlands occupy about 2 - 6% of the Earth's surface area and store approximately 20% of the global organic C qualifying them as one of the most efficient C stores [133] [134]. However, extreme weather conditions have significantly disrupted the rate of CS in wetlands. Increased precipitation, prolonged droughts, heavy floods, and tropical storms are altering wetland hydrology, vegetation, and structure, thereby impairing C storage. Intense precipitation and floods, for instance, reduce a wetland's ability to store C by causing erosion and disturbing C-rich soils, which releases C into the water and atmosphere. A notable example of coastal marshes in Louisiana is the historical loss of the wetland CS capacity by 1.0 Tg C yr^{-1} which projected a 50% reduction in C storage in the next 50 years if restoration is not done [135]. Conversely, long-term droughts convert wetlands into C sources by exposing organic matter to oxygen, which accelerates its decomposition and CO_2 and CH_4 release. This was observed in the Okavango Delta, where severe droughts caused a decline in C accumulation due to organic matter oxidation. Rising temperatures further exacerbate these effects by destroying vegetation and biodiversity, leaving only heat-resistant species that disrupt the C cycle. For instance, in Indonesian tropical peatlands, vegetation destruction and decomposition have led to significant C losses [136]. Similarly, wildfires, such as those in Australian bushfires, release GHG emissions and destroy vegetation that would otherwise aid in C uptake. In summary, climate change contributes to the degradation of wetlands by altering the hydrology, increasing evaporation, and causing extreme droughts and floods. This ultimately reduces the wetlands' ability to sequester C and filter water, worsening water quality and increasing GHG emissions.

5.2. Ocean Carbon Sequestration in the Changing Climate

The ocean is considered as a primary C sink which stores substantial amounts of CO_2 [136]. The ocean is usually one of those water resources majorly affected by changes in climate and is also considered as one of the main contributors to mitigation of climate change. Carbon dioxide is absorbed by the ocean annually, accounting for about 25% of emissions [137]. This process involves a flux that moves in two directions: positive when CO_2 is released into the atmosphere and negative when it is absorbed by the ocean. Absorption is more significant in colder, nutrient-rich waters compared to warmer regions. Literature indicates that by 2100, ocean chemistry is expected to change, which might lead to lower pH levels and increased acidity [138].

The capacity of the ocean's CS is deteriorating due to the extreme weather events such as increased precipitation, temperature, storms and intense floods. Some parts of the ocean have reduced light penetration and disrupted phytoplankton photosynthesis which lessens the biological C uptake. This majorly results from heavy precipitation and coastal flooding which aids high runoff containing sediments and nutrients. On the other hand, high sea surface temperatures usually reduce the rate of solubility of CO_2 and escalate ocean stratification which reduces C drawdown. The rising temperatures also lead to loss of marine biodiversity and bleaching of coral reefs which release stored C to the atmosphere. In summary, extreme weather events disrupt both the physical and biological processes regulating C cycling in the ocean by reducing CO_2 absorption, enhancing C release, and diminishing the ocean's capacity to store C, thereby compromising its role in maintaining the C cycle.

5.3. Increasing CO_2 Impacts on Water Ecosystems

The major consequences of increased CO_2 in the atmosphere are global temperatures and frequent heat waves which result in melting glaciers, rise of sea levels and variations in precipitation trends. Accumulation of CO_2 at the ecosystem level contributes to the acidification of water bodies. When CO_2 dissolves in water, it forms carbonic acid, which dissociates to release hydrogen ions, thereby lowering water pH. This process has significant biological implications such as accelerating the dissolution of skeletons in aquatic species such as corals and mollusks. Additionally, oxygen transport is impaired, and metabolic processes are reduced, potentially leading to the death and sometimes extinction of aquatic life. These changes ultimately result in the deterioration of water characteristics [138]. Elevated temperatures accelerate the desiccation of vegetation, creating conditions conducive to wildfires. These fires disrupt flora dispersal, reduce evapotranspiration rates critical for rainfall formation, lower water levels in rivers and lakes, and degrade water quality through increased sedimentation and impaired natural filtration systems.

6. Remediation Strategies for Adapting to and Mitigating Climate Change Impacts on Water Resource Degradation

6.1. Adaptation Strategies

Globally, climate change can qualitatively and quantitatively deteriorate water resources. Adaptation measures are crucial for reducing the impact of disasters like droughts and floods on water ecosystems [139] [140]. The main objective of adapting to climate change is to improve resilience, enable sustainable water availability and quality under altering conditions (**Figure 3**). One impactful approach to address the challenges of unsustainable water resources is the use of climate smart technologies which involve innovative tools and practices which help to ensure water sustainability, food security, adaptation to climate change and minimized GHG emissions. These strategies include rainwater harvesting, desalination, wastewater recycling, nature-based systems, and controlled aquifer recharge can help mitigate resource depletion by replenishing groundwater and providing alternative water sources [141] [142] (**Figure 3**). For instance, a study in arid and semi-arid areas showed enhancement of groundwater availability through climate smart rainwater harvesting and managed aquifer recharge in Egypt. This study revealed an aquifer recharge of 24.3, 28.8, 36.7 and 49.7 mcm with groundwater storage of 11.8%, 32.1%, 69%, 127.4% respectively for return periods of 10, 25, 50 and 100 years indicating a sustainable support of freshwater [143].

Another approach is improving water use efficiency, which is defined as the ratio of productivity per unit use of water. This commonly applies in agricultural systems that use most of global water. Farmers can opt to adopt techniques such as drip irrigation which can help moderate the amount of water being used for irrigation. Such systems have been implemented by Israel national irrigation committee to help control the rate of water misuse in their region [144]. Implementing community awareness and innovative water-saving technologies in urban areas can reduce leakages and promote the adoption of water-efficient devices, such as low-flow fixtures and recycling systems, in households and industries.

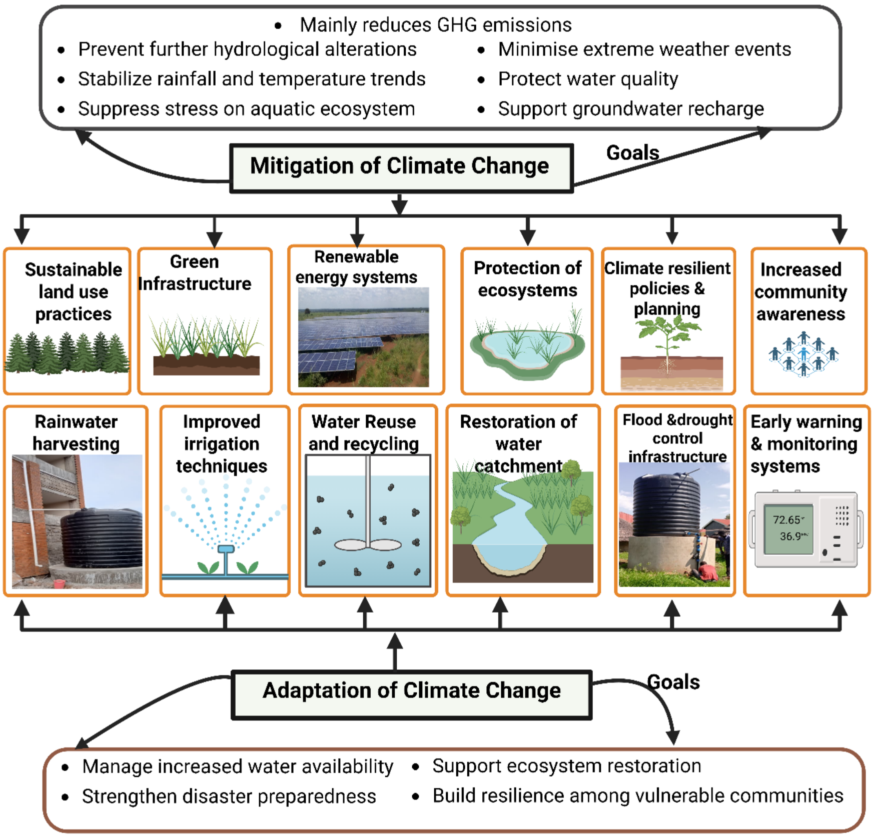

Figure 3. Schematic diagram summarizing the proposed mitigations and adaptation of climate change effects on water resources.

Advanced wastewater treatment technologies, including nutrient removal processes for N and P, along with effective disinfection methods, are essential for safeguarding water quality by reducing pollutant levels in water resources. Establishing buffer zones around wetlands and water sources can mitigate direct contamination from agricultural runoffs, thereby minimizing eutrophication. In China, natural infiltration systems have been employed to reduce urban flooding and control aquifer recharge, achieving a 75% annual runoff reduction through bioretention (34.5%) and sunken green spaces (46%) [145]. Rise of sea levels often leads to the salinization of freshwater bodies. Climate-smart adaptation strategies to address water salinization include controlled aquifer recharge and pumping, cultivating salt-tolerant crops such as rice, wheat, and vegetables, restoring mangroves and wetlands as natural barriers, and employing renewable energy-driven desalination techniques. In Israel, the National Water Management has incorporated desalination and recycling to help suppress the decreasing scarcity of freshwater resources with more than 87% of wastewater being used for agriculture and the five desalination plants providing about 80% of urban water used [146] [147].

Lastly, focus can be put on preparedness and capacity building. For flooding, there should be implementation of flood adaptation techniques such as restoring flood plains, levees and flood walls, flood warning systems, providing flood hazard maps and flood forecasting systems (**Figure 3**). Communities can accommodate drought through integration of climate resilient infrastructures like micro scale irrigation systems depending on groundwater pumping, and growing drought resistant crop varieties like sorghum, cassava and millet.

6.2. Mitigation Strategies

Climate change mitigation involves addressing its root causes, primarily by reducing GHG emissions that significantly impact water sustainability. Water resources act as both sources and sinks of GHGs. Mitigation strategies include conserving ecosystems such as wetlands, which serve as critical C sinks, support CS, regulate floods, and naturally filter contaminants from rivers, lakes, and oceans [136]. Increased and enhanced CS activity plays a crucial role in addressing global climate change through the reduction of levels of CO_2 which trap heat in the atmosphere [148]. Coastal ecosystems, including mangroves, seagrasses, and salt marshes, are crucial for shoreline protection. They mitigate the impacts of storm surges and help prevent salinity intrusion, highlighting their importance in maintaining coastal resilience.

Table 1. Possible outcomes from implementation of different adaptation and mitigation measures.

S/No	Measure	Adaptation	Mitigation
1	Urban green infrastructure	Minimizes flooding	Captures C
2	Reforestation of watersheds	Enhances infiltration and regulates water	Absorbs CO_2
3	Renewable-powered desalination	Guarantees freshwater security	Reduces the intensity of emissions
4	Nature-based solutions	Enhancing resilience	Reduction of emissions

Sustainable agricultural practices and proper land use management are key measures for mitigating climate change impacts on water resources (**Figure 3**). For instance, optimization of fertilizer use especially nitrogenous fertilizers using the 4R (right rate, source, timing and placement) strategy, and irrigation can be practiced to minimize the release of N_2O and nutrient pollution from agricultural lands. Additionally, reliance on synthetic fertilizer production can be minimized through the recycling of N and P in agricultural systems (**Table 1**).

Lastly, climate change-driven water degradation can be mitigated by integrating the circular water-energy nexus which includes the recovery of nutrients from wastewater such as the extraction of biogas from sludge treatment. This can facilitate the transition to renewable energy systems, thereby reducing GHG emissions. Awareness campaigns play a critical role in educating vulnerable communities about the conservation of aquatic ecosystems and the prevention of their degradation. These efforts ensure the preservation of essential ecological functions within these ecosystems [148].

7. Challenges, Opportunities and Research Gaps in Enforcing Mitigation of Climate Change-Induced Water Resource Degradation

Water resources are one of the ecosystems with a high vulnerability to climate change impacts. Several mitigation and adaptation techniques like climate-smart technologies, renewable energy transitions, CS resilient agriculture and ecosystem-based approaches suggested above are currently facing several challenges. One of the critical challenges is the unpredictability of climate models. Models such as Global Climate Models (GCM) and Regional Climate Models (RCM) which produce important projections often have different outputs depending on assumptions and spatial resolution which poses a difficulty in decision making. Secondly, climate-smart projects often demand substantial financial resources for implementation, particularly in developing nations facing significant water-related challenges. These countries frequently lack adequate finance and capital to support such climate change-mitigation initiatives. Additionally, critical infrastructure, including water supply systems, dams, and irrigation networks, often lacks design features that account for climate change and extreme weather events. Consequently, ensuring resilience against flooding and prolonged droughts becomes both complex and costly. Finally, the misalignment between local realities and the advanced technologies innovated by developed countries has created a substantial lag in addressing climate-related challenges in many communities.

Despite these challenges, there are numerous opportunities for water resilience to enhance sustainable management and conservation of water resources. Utilizing renewable energy sources reduces water demand by hydropower stations and mitigates GHG emissions. Reforestation and improved soil management enhance hydrological stability by improving water infiltration and reducing erosion. Projecting hydrological trends and implementing early warning systems improve community preparedness for floods and droughts. Effective irrigation, water monitoring, wastewater reuse, and ecosystem-based management strategies improve efficiency and productivity. The adoption of climate-smart techniques and mitigation approaches supports the sustainability of water resources, minimizing the impacts of extreme weather events.

Research gaps exist in understanding how wildfires, intense storms, and short-duration heatwaves independently impact water quality and hydrological characteristics across both prolonged and immediate timescales. Secondly, there is limited temporal data on the interrelationships between extreme weather events, pollutant persistence and nutrient accumulation in water resources. Furthermore, damage severity thresholds are not known. Assessing the timing and frequency of these extreme events is essential to enhance preparedness in vulnerable communities. There is a need to study how sequential, or compound extreme events influence the transport of pollutants, biogeochemical cycling, and cumulative water quality deterioration. Additionally, it is essential to determine specific temperature or pollutant concentration thresholds that could trigger irreversible ecosystem damage in key aquatic systems.

8. Conclusion

Climate change significantly exacerbates water resources degradation by altering the hydrological cycle, driven by rising temperatures, shifting precipitation patterns, and increased extreme weather events. These changes, compounded by the accumulation of GHGs such as CO_2, CH_4 and N_2O, disrupt the natural equilibrium of the Earth's systems. The resulting challenges include declining water levels, sedimentation, nutrient loading, pollutant accumulation, salinity, and eutrophication, which degrade the quality and availability of water in rivers, lakes, wetlands, and oceans. These impacts increase public health risks, food insecurity, and economic instability, while compromising ecosystem productivity and the C sequestration capacity of wetlands, transforming them from C sinks into sources of CO_2 and CH_4. To address these challenges, an integrated approach that considers hydrological, biogeochemical, and ecological dynamics is essential for effective water resource conservation. Mitigation and adaptation strategies, including climate-smart technologies, renewable energy transitions, conservation agriculture (e.g., agroforestry, conservation tillage, and biochar application), and ecosystem-based solutions, offer pathways to enhance climate resilience and ensure sustainable water security and C management in water resources. This review underscores the urgent need for action to mitigate the impacts of climate change on water resources, to promote their resilience, equity, and long-term sustainability.

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Conflicts of Interest

No conflict of interest declared.

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