

Climate Change and the Hydrologic Cycle: Emerging Patterns, Process Alterations, and Implications for Sustainable Water Resources Management

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Abstract

Climate change is profoundly altering the global hydrologic cycle, affecting the movement, storage, and quality of water across atmospheric, terrestrial, and aquatic systems. Rising global temperatures, changing precipitation patterns, increasing atmospheric evaporative demand, and intensifying hydroclimatic extremes are reshaping key hydrological processes, including evapotranspiration, soil moisture dynamics, runoff generation, streamflow regimes, groundwater recharge, and water quality. This review synthesizes recent advances in understanding the impacts of climate change on the hydrologic cycle, drawing upon contemporary literature published between 2023 and 2026. The review examines how warming-induced changes in atmospheric moisture transport and precipitation variability are increasing the frequency and intensity of floods, droughts, heatwaves, and compound hydroclimatic events. It further explores the implications of climate change for groundwater sustainability, freshwater ecosystems, water quality, and ecosystem services. Emerging evidence indicates that climate change is not only intensifying the hydrologic cycle but also increasing its spatial and temporal variability, thereby increasing uncertainty in water availability and resource management. The review highlights major research gaps related to groundwater–climate interactions, compound extremes, human–water feedback, and ecosystem resilience. Additionally, it evaluates adaptation and mitigation strategies, including integrated water resources management, nature-based solutions, climate-smart agriculture, sustainable groundwater management, and the application of artificial intelligence and digital-twin technologies for climate-resilient water governance. The findings emphasize that future water security will depend on integrating scientific innovation, adaptive management, and policy interventions to address increasingly non-stationary hydrological conditions. Strengthening interdisciplinary research and climate-informed water management frameworks will be essential for enhancing resilience and ensuring the sustainable use of freshwater resources in a rapidly changing climate.

Keywords: Precipitation variability, groundwater recharge, hydroclimatic extremes, water quality, climate resilience, water security, digital twins

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INTRODUCTION

Water is the fundamental medium through which climate change manifests its impacts on natural and human systems. The hydrologic cycle, encompassing evaporation, transpiration, condensation, precipitation, infiltration, runoff, and groundwater recharge, regulates the distribution and availability of freshwater resources worldwide. Changes in any component of this cycle can influence water security, ecosystem functioning, agricultural productivity, energy

generation, and socioeconomic development. Recent evidence indicates that anthropogenic climate change is fundamentally altering the hydrologic cycle, resulting in unprecedented changes in water availability, hydrological extremes, and watershed processes worldwide (Jánosi et al., 2025; Bărbulescu, 2025) [1, 2].

Recent studies have shown that the global water cycle is becoming increasingly erratic, characterised by frequent transitions between extremely wet and extremely dry conditions. The World Meteorological Organisation reported that the hydrologic cycle experienced unprecedented instability during 2023–2025, with many river basins simultaneously experiencing severe floods and droughts. Such hydroclimatic variability has been linked to rising temperatures, altered atmospheric circulation patterns, and increasing atmospheric water-holding capacity (Adeyeri, 2025) [3].

One of the most evident manifestations of climate change is the alteration of precipitation patterns. Observational and modelling studies indicate that precipitation is becoming increasingly concentrated in high-intensity events, while many regions are experiencing longer dry periods between rainfall episodes. These shifts influence watershed hydrology by increasing surface runoff, reducing infiltration opportunities, accelerating soil erosion, and enhancing flood risks. Simultaneously, declining rainfall reliability contributes to groundwater depletion, agricultural drought, and ecosystem stress. Recent assessments suggest that future precipitation variability may exceed changes in mean precipitation, emphasising the growing importance of hydrological extremes in climate adaptation planning (Ji et al., 2025) [4].

Climate-induced changes in evapotranspiration and soil moisture are also becoming increasingly evident. Rising temperatures increase atmospheric evaporative demand, leading to enhanced evapotranspiration rates and declining soil moisture storage in many regions. Recent global analyses have revealed substantial reductions in terrestrial water storage and soil moisture over the past two decades, with some studies suggesting that ongoing drying trends may persist for decades even under moderate climate mitigation scenarios. Soil moisture depletion not only affects agricultural productivity but also alters land–atmosphere feedback mechanisms that influence regional precipitation and temperature patterns (Bărbulescu, 2025) [2].

Groundwater systems, which provide nearly half of the world's drinking water and a significant proportion of irrigation supply, are particularly vulnerable to climate change. Reduced recharge rates, increasing evapotranspiration losses, changing precipitation patterns, and rising water demand collectively threaten groundwater sustainability. Recent satellite-based assessments indicate widespread freshwater depletion across major aquifer systems, particularly in South Asia, North America, and parts of Europe. Furthermore, the expansion of large-scale "mega-drying" regions driven by groundwater extraction and climate-induced evapotranspiration has emerged as a growing global concern (Zhang, 2025) [5].

Climate change is also amplifying the frequency and intensity of hydroclimatic extremes. Increasing evidence points toward the emergence of "hydroclimatic whiplash," characterised by rapid transitions between drought and flood conditions. Recent modelling studies suggest that such abrupt shifts may more than double in frequency under high-emission warming scenarios, posing substantial challenges for conventional water resources planning and infrastructure design. The increasing frequency of compound events, including simultaneous heatwaves, droughts, and floods, further underscores the complex nature of climate–hydrology interactions (Rico-Bordera et al., 2026) [6].

Despite substantial advances in climate science, considerable uncertainties remain regarding regional hydrological responses to climate change. These uncertainties arise from differences among climate models, hydrological model structures, land-use changes, and human interventions such as irrigation,

reservoir operations, and groundwater abstraction. Recent developments in high-resolution climate modelling, Earth system models, satellite observations, artificial intelligence, and physics-informed hydrological modelling offer new opportunities to improve the understanding and prediction of climate-induced hydrological changes (Sarwar et al., 2026; Ji et al., 2025) [7, 4].

Given the accelerating pace of hydroclimatic change and its implications for water security, ecosystem resilience, and sustainable development, a comprehensive understanding of climate change impacts on the hydrologic cycle is essential. Therefore, this study synthesises recent advances in understanding climate-induced alterations in hydrological processes, evaluates their implications for water resources and ecosystems, and identifies emerging research directions for improving climate-resilient water management under future warming scenarios.

CLIMATE CHANGE AND THE HYDROLOGIC CYCLE: CONCEPTUAL FRAMEWORK

The Natural Hydrologic Cycle

The hydrologic cycle represents the continuous circulation of water among the atmosphere, oceans, land surface, cryosphere, and subsurface environments. Driven primarily by solar radiation and gravitational forces, water evaporates from oceans, lakes, rivers, and soil surfaces, while transpiration from vegetation contributes additional moisture to the atmosphere. Atmospheric water vapour subsequently condenses to form clouds and precipitation, which returns water to terrestrial and aquatic systems. Following precipitation, water may infiltrate into the soil, recharge groundwater aquifers, be stored as snow and ice, or flow as surface runoff toward rivers, lakes, and oceans.

The hydrologic cycle plays a critical role in regulating global energy exchange, nutrient transport, ecosystem functioning, and freshwater availability. Any perturbation in atmospheric temperature, humidity, precipitation, or circulation patterns can propagate through the entire hydrological system, producing cascading effects on water resources and environmental sustainability (Guan et al., 2024; Bărbulescu, 2025) [8, 2].

Climate-Driven Intensification of the Hydrologic Cycle

One of the most robust consequences of anthropogenic climate change is the intensification of the hydrologic cycle. Rising global temperatures increase the atmosphere's capacity to hold water vapour according to the Clausius–Clapeyron relationship, which predicts an approximate 7% increase in atmospheric moisture-holding capacity for every 1°C increase in temperature. Enhanced atmospheric moisture leads to increased evaporation and evapotranspiration rates, stronger moisture transport, and greater precipitation potential. Recent studies demonstrate that anthropogenic climate change has already strengthened the terrestrial water cycle through increased precipitation, enhanced atmospheric moisture transport, and intensified land-atmosphere interactions. Guan et al. (2024) [8] reported that human-induced climate change has accelerated intensification of the terrestrial water cycle globally, with particularly rapid increases in traditionally dry regions. These findings challenge the conventional "wet-gets-wetter and dry-gets-drier" paradigm and indicate increasingly complex hydrological responses to climate forcing.

Hydrological intensification is characterised not only by increases in mean water fluxes but also by enhanced variability and extremes. Increasing atmospheric moisture promotes more intense rainfall events, while higher temperatures increase evaporative demand and accelerate soil moisture depletion. Consequently, regions may experience both severe flooding and prolonged droughts within relatively short time periods, a phenomenon increasingly described as hydroclimatic volatility or hydrological whiplash (Swain et al., 2025) [9].

Major Climate Drivers Influencing Hydrological Processes

Climate change influences the hydrologic cycle through a range of interconnected atmospheric, terrestrial, and cryospheric processes that collectively alter water availability, storage, and movement across landscapes. Rising air temperature is the primary driver of hydrological change, enhancing evaporation from water bodies, increasing plant transpiration, accelerating snow and glacier melt, and increasing atmospheric moisture-holding capacity. Higher temperatures also elevate vapour pressure deficits, intensifying atmospheric moisture demand and increasing water losses from soils and vegetation (Bărbulescu, 2025) [2]. Simultaneously, a warmer atmosphere contains greater amounts of water vapour, thereby strengthening moisture transport and precipitation. Climate change also modifies large-scale atmospheric circulation systems, including monsoons, jet streams, atmospheric rivers, and teleconnections such as the El Niño–Southern Oscillation (ENSO), thereby influencing the spatial and temporal distribution of precipitation and runoff across river basins worldwide (Guan et al., 2024) [8].

Emerging Characteristics of the Climate-Modified Hydrologic Cycle

Recent observations indicate that the climate-modified hydrologic cycle is characterized by increased atmospheric water vapour concentrations, enhanced evaporation, more intense precipitation events, greater rainfall variability, accelerated evapotranspiration, declining soil moisture, reduced snowpack and glacier storage, altered groundwater recharge dynamics, and a growing frequency of compound drought–flood events. These changes are contributing to increased uncertainty in future water availability and are fundamentally altering the temporal and spatial distribution of freshwater resources.

The World Meteorological Organization has highlighted that the global water cycle is becoming increasingly erratic, with many river basins experiencing unprecedented transitions between severe droughts and extreme floods. Such patterns suggest that future hydrological systems will be defined less by gradual shifts in long-term average conditions and more by increasing variability, extremes, and hydroclimatic instability. Collectively, these developments demonstrate that climate change is reshaping the hydrologic cycle through interconnected atmospheric, terrestrial, and cryospheric processes. Understanding these evolving dynamics is critical for assessing impacts on key hydrological components, including precipitation, evapotranspiration, soil moisture, streamflow, groundwater resources, and water security, thereby informing effective adaptation and management strategies under a changing climate.

Figure 1 presents a conceptual framework illustrating the major pathways through which climate change modifies the hydrologic cycle. Rising temperatures, altered atmospheric circulation, and cryospheric changes influence fundamental hydrological processes, including precipitation, evapotranspiration, soil moisture, runoff, streamflow, groundwater recharge, and water quality. These interconnected changes ultimately intensify hydroclimatic extremes and increase pressures on water resources, ecosystems, and human societies.

IMPACTS OF CLIMATE CHANGE ON PRECIPITATION DYNAMICS

Changing Global Precipitation Patterns

Precipitation is one of the most climate-sensitive components of the hydrologic cycle. Rising global temperatures are altering atmospheric moisture storage, circulation patterns, cloud microphysics, and storm dynamics, resulting in significant changes in the amount, intensity, frequency, and spatial distribution of precipitation. Recent observations indicate that global warming is strengthening atmospheric moisture transport and increasing precipitation variability across many regions of the world.

The Clausius-Clapeyron relationship largely governs the physical basis for these changes, which states that atmospheric water-holding capacity increases by approximately 7% for every 1°C increase in air temperature.

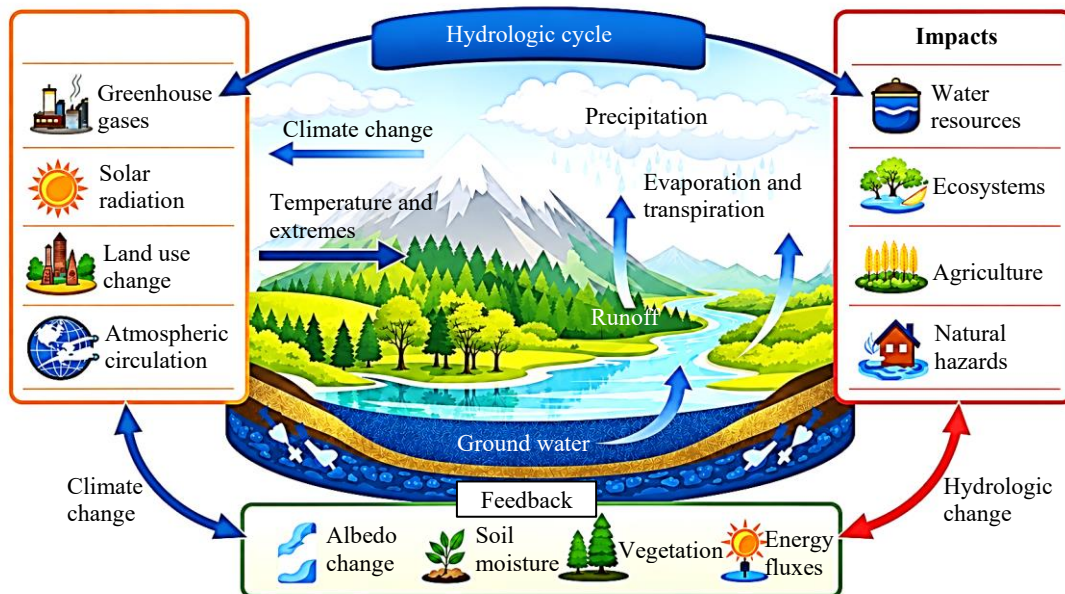


Figure 1. Conceptual framework: Climate change–hydrologic cycle interactions.

Consequently, a warmer atmosphere can transport and release greater amounts of moisture, leading to more intense precipitation events when favourable meteorological conditions prevail. Recent studies suggest that climate change is accelerating the intensification of the global water cycle, resulting in stronger wet and dry extremes simultaneously.

Intensification of Extreme Rainfall Events

The increasing frequency and intensity of heavy precipitation events is one of the most robust signals of climate change. Enhanced atmospheric moisture availability provides greater fuel for convective storms, tropical cyclones, atmospheric rivers, and monsoon systems. Recent analyses indicate widespread increases in hourly and daily rainfall intensity across many regions, even where annual precipitation trends remain weak.

Climate Central's assessment of long-term rainfall records demonstrated that rainfall intensity has increased significantly in most monitored locations due to anthropogenic warming. Similarly, recent studies using climate-model ensembles project substantial increases in extreme precipitation under future warming scenarios, particularly in tropical and subtropical regions. These findings suggest that flood-producing storms may become more severe even in regions where average rainfall changes are relatively modest.

Shifts in Precipitation Seasonality

Climate change is altering not only rainfall intensity but also its seasonal distribution. Numerous regions are experiencing shifts in the onset, duration, and termination of rainy seasons. Such changes have important implications for agriculture, reservoir operations, groundwater recharge, and ecosystem functioning.

In monsoon-dominated regions, recent studies indicate increasing interannual variability, delayed onset, early withdrawal, and irregular rainfall distribution. Although total seasonal precipitation may remain relatively stable, rainfall is increasingly concentrated into shorter, more intense periods. This phenomenon reduces the effectiveness of rainfall for groundwater recharge and agricultural utilisation while increasing flood risks.

Changes in seasonality also influence snow-dominated watersheds. Rising temperatures are causing a larger proportion of winter precipitation to fall as rain rather than snow. Consequently, snow accumulation decreases while winter runoff increases, fundamentally altering seasonal streamflow regimes. Such changes are particularly evident in high-altitude and high-latitude regions where snowpack historically served as a natural water storage system.

Hydroclimatic Whiplash and Precipitation Extremes

An emerging consequence of climate change is the increasing occurrence of hydroclimatic whiplash, characterised by rapid transitions between extremely wet and extremely dry conditions. Recent research indicates that such events have increased substantially since the mid-twentieth century and are projected to become more frequent under future warming scenarios. These abrupt shifts pose severe challenges for water management systems that were designed under assumptions of relatively stable climatic conditions.

Hydroclimatic whiplash can occur when intense rainfall follows prolonged drought. Dry soils often become hydrophobic and less able to absorb rainfall, leading to increased runoff and flash flooding. Simultaneously, water storage systems may struggle to balance competing demands for flood control and drought mitigation. The increasing frequency of such compound events underscores the need for adaptive, flexible water management strategies.

Regional Variability in Precipitation Responses

Although precipitation intensification is a global phenomenon, regional responses vary considerably due to differences in atmospheric circulation, topography, ocean-atmosphere interactions, and land-surface characteristics. Tropical regions generally exhibit increasing precipitation extremes, whereas many subtropical regions face declining rainfall and increasing drought frequency. Mountain regions often exhibit complex responses driven by interactions among temperature, elevation, and moisture transport.

Recent assessments by the World Meteorological Organisation indicate that only about one-third of the world's river basins exhibited near-normal hydrological conditions during 2024. Many basins simultaneously experienced severe droughts and floods, demonstrating the increasing instability of regional precipitation regimes under climate change. Such observations reinforce the importance of basin-scale investigations for understanding local hydrological responses to global climate forcing.

CLIMATE CHANGE IMPACTS ON EVAPOTRANSPIRATION AND SOIL MOISTURE DYNAMICS

Evapotranspiration (ET) and soil moisture are fundamental components of the hydrologic cycle that regulate the exchange of water and energy between the land surface and atmosphere. ET represents the combined loss of water from soil and water surfaces through evaporation and from vegetation through transpiration. In contrast, soil moisture serves as a critical intermediary between precipitation, runoff, groundwater recharge, and plant water uptake. Climate change is substantially altering both processes through rising temperatures, changing precipitation regimes, elevated atmospheric carbon dioxide concentrations, and shifts in vegetation dynamics.

Recent studies suggest that increasing atmospheric evaporative demand is one of the most pervasive consequences of global warming, affecting nearly all climatic regions. Changes in ET and soil moisture directly influence drought development, agricultural productivity, groundwater recharge, ecosystem resilience, and watershed hydrology, making them critical indicators of climate-induced hydrological change (Bărbulescu, 2025; Bharghavi et al., 2025) [2, 10].

Climate Controls on Evapotranspiration

Several climatic and environmental factors, including air temperature, solar radiation, humidity, wind speed, vegetation characteristics, and soil water availability, govern evapotranspiration. Among these, temperature plays a dominant role in regulating atmospheric evaporative demand. As global temperatures rise, the atmosphere's capacity to absorb moisture increases, leading to higher vapour pressure deficits (VPDs). VPD represents the difference between the amount of moisture the atmosphere can hold and the amount it currently contains. Elevated VPD creates stronger atmospheric demand for water, accelerating evaporation from water bodies and transpiration from vegetation. Consequently, potential evapotranspiration is increasing across many regions worldwide.

Recent global analyses indicate that atmospheric evaporative demand has increased significantly during the past four decades, with particularly rapid growth observed in arid and semi-arid regions. Such increases are expected to continue under future warming scenarios, intensifying water losses from terrestrial ecosystems and reducing water availability for other hydrological processes (Yao et al., 2026) [11].

Rising Atmospheric Evaporative Demand

Increase in atmospheric evaporative demand (AED) is one of the clearest hydrological responses to climate change. AED reflects the atmosphere's capacity to remove water from the land surface and has emerged as a major driver of drought intensification worldwide. Recent studies have demonstrated that warming-induced increases in AED have contributed substantially to drought severity, even in regions where precipitation has not declined significantly. This phenomenon, often referred to as "hot drought," occurs when elevated temperatures accelerate evapotranspiration and soil moisture depletion, thereby intensifying water deficits. Evidence from North America, Europe, Asia, and Australia suggests that increasing AED is becoming a dominant factor controlling drought occurrence and persistence (Vicente-Serrano et al., 2022) [12]. Under future climate scenarios, rising AED is projected to exacerbate water stress across many river basins, increasing irrigation demands, reducing environmental flows, and intensifying competition among water users.

Soil Moisture Responses to Climate Change

Soil moisture is a key indicator of watershed health and hydrological resilience because it integrates the effects of precipitation, evapotranspiration, infiltration, runoff, and vegetation dynamics. Changes in soil moisture influence agricultural productivity, ecosystem functioning, groundwater recharge, and streamflow generation. Recent satellite observations and land-surface modelling studies reveal widespread declines in soil moisture across many regions during the past two decades. These declines are largely attributed to increasing temperatures, enhanced evaporative demand, altered rainfall patterns, and more frequent droughts. Although some high-latitude regions have experienced localised increases in soil moisture due to enhanced precipitation, drying trends dominate many tropical, subtropical, and temperate regions.

The reduction of soil moisture has important hydrological consequences. Drier soils decrease groundwater recharge potential, reduce baseflow contributions to rivers, and increase susceptibility to agricultural drought. Furthermore, prolonged soil moisture deficits can alter vegetation structure and reduce ecosystem productivity, creating feedback loops that further influence regional climate and hydrology.

Land–Atmosphere Feedback Mechanisms

Climate change impacts on evapotranspiration and soil moisture are amplified through complex land–atmosphere feedback. Soil moisture influences the partitioning of available energy between sensible heat and latent heat fluxes. When soils are sufficiently moist, a substantial portion of incoming energy is used for evapotranspiration. However, under dry conditions, evaporation consumes less energy, resulting in

greater surface heating and higher air temperatures. This feedback mechanism can intensify heatwaves and droughts. Reduced soil moisture increases surface temperatures, which in turn elevate evaporative demand and further deplete soil water reserves. Such positive feedback loops have been observed during major drought events across Europe, North America, and South Asia and are expected to strengthen under continued warming (Miralles et al., 2024) [13].

Vegetation responses further complicate these interactions. Elevated atmospheric CO₂ concentrations may improve plant water-use efficiency by reducing stomatal conductance, potentially decreasing transpiration rates. However, enhanced vegetation growth may offset these reductions through increased leaf area and biomass. Consequently, the net impact of elevated CO₂ on evapotranspiration remains uncertain and varies across ecosystems.

Implications for Agriculture and Ecosystems

Changes in evapotranspiration and soil moisture directly affect agricultural systems. Increasing evaporative demand raises crop water requirements, while declining soil moisture reduces water availability during critical growth periods. These combined effects can lower crop yields, increase reliance on irrigation, and heighten vulnerability to agricultural drought. Recent studies project substantial increases in irrigation demand across many agricultural regions under future warming scenarios. In water-scarce regions, such increases may exacerbate groundwater depletion and intensify competition among agricultural, domestic, and industrial sectors.

Natural ecosystems are similarly affected. Persistent soil moisture deficits can reduce vegetation productivity, alter species composition, increase wildfire susceptibility, and disrupt ecosystem services. Forests, wetlands, and grasslands may experience significant changes in hydrological functioning as climate change reshapes regional water balances.

Future Projections and Uncertainties

Climate model projections consistently indicate increasing evapotranspiration demand and declining soil moisture across many regions during the twenty-first century. However, substantial uncertainties remain regarding the magnitude and spatial distribution of these changes. Differences among climate models, land-surface parameterisations, vegetation responses, and future emission scenarios contribute to uncertainty in projections.

Emerging technologies such as satellite remote sensing, Earth system models, machine learning algorithms, and digital-twin hydrological frameworks are improving the ability to monitor and predict ET and soil moisture dynamics at regional and global scales. These advances are expected to enhance drought forecasting, water resource planning, and climate adaptation strategies.

CLIMATE CHANGE IMPACTS ON RUNOFF AND STREAMFLOW REGIMES

Runoff and streamflow constitute the primary mechanisms through which water is transported across landscapes and river networks. These hydrological components integrate the combined effects of precipitation, evapotranspiration, soil moisture, land cover, groundwater interactions, and watershed characteristics. Consequently, alterations in climate variables directly influence the magnitude, timing, frequency, and variability of river flows. As climate change continues to modify precipitation regimes, evapotranspiration rates, snowmelt dynamics, and groundwater recharge processes, significant changes in runoff generation and streamflow behaviour are being observed across river basins worldwide.

Recent studies indicate that streamflow responses to climate change are highly heterogeneous, reflecting regional differences in climatic conditions, topography, watershed characteristics, and human interventions. While some regions are experiencing increasing annual runoff and flood frequency, others are facing declining river discharge, reduced baseflow, and heightened hydrological drought risk. These contrasting responses highlight the complexity of climate–hydrology interactions and underscore the need for basin-specific assessments (Gudmundsson et al., 2024; Pokhrel et al., 2025) [14, 15].

Climate-Induced Changes in Runoff Generation

Runoff generation is fundamentally controlled by the balance between precipitation inputs and water losses through evapotranspiration and infiltration. Climate change influences each of these processes, thereby altering both the quantity and pathways of runoff production. Increasing precipitation intensity is enhancing surface runoff generation in many watersheds. High-intensity rainfall events frequently exceed soil infiltration capacities, leading to infiltration-excess runoff and rapid increases in streamflow. This phenomenon is particularly pronounced in urbanised and degraded watersheds where impervious surfaces and soil compaction further reduce infiltration opportunities. Consequently, many regions are experiencing greater runoff coefficients and more frequent flash floods despite relatively modest changes in annual rainfall totals.

Conversely, increasing evapotranspiration and prolonged dry periods can reduce antecedent soil moisture and diminish runoff generation during non-extreme precipitation events. In water-limited environments, declining soil moisture often results in lower annual runoff and reduced water availability. Thus, climate change is simultaneously increasing flood-generating runoff during extreme storms while reducing runoff during dry periods, contributing to greater hydrological variability. Recent global assessments suggest that runoff variability is increasing faster than mean annual runoff, indicating that future hydrological systems may be characterised by greater extremes rather than uniform changes in water availability (Liang et al., 2026; Yao et al., 2026) [16, 11].

Alterations in Streamflow Magnitude and Timing

One of the most significant hydrological consequences of climate change is the alteration of streamflow regimes. Changes in precipitation seasonality, snowmelt dynamics, and evapotranspiration rates are modifying both the magnitude and timing of river discharge. In many temperate and mountainous regions, streamflow peaks are occurring earlier in the year due to accelerated snowmelt and reduced snowpack accumulation. Historically, snowpacks functioned as natural reservoirs that gradually released water during spring and summer. Rising temperatures are reducing snow storage and increasing winter runoff, resulting in earlier peak flows and reduced dry-season water availability (Soomro et al., 2024) [17].

In rainfall-dominated basins, streamflow responses are largely governed by changes in precipitation intensity and seasonality. Increased rainfall concentration within shorter periods often generates larger flood peaks, whereas longer dry intervals contribute to declining baseflow and lower dry-season discharge. Such shifts have important implications for reservoir operation, irrigation supply, hydropower generation, and ecosystem sustainability (Gudmundsson et al., 2026; Wang et al., 2024) [14, 18].

CLIMATE CHANGE IMPACTS ON GROUNDWATER RECHARGE AND STORAGE

Groundwater constitutes approximately 99% of the Earth's liquid freshwater and supplies nearly half of global drinking water demand, about 40% of irrigated agriculture, and a substantial proportion of industrial water requirements. As a strategic freshwater reserve, groundwater plays a critical role in sustaining river baseflows, supporting ecosystems, buffering drought impacts, and maintaining water security during

periods of climatic variability. However, climate change is increasingly altering groundwater recharge processes, aquifer storage dynamics, and groundwater–surface water interactions, thereby threatening the long-term sustainability of groundwater resources worldwide.

Unlike surface water systems, groundwater responds relatively slowly to climatic changes due to delayed recharge processes and long residence times. Nevertheless, recent studies indicate that climate-driven changes in precipitation patterns, evapotranspiration rates, soil moisture dynamics, and extreme events are significantly influencing groundwater systems across diverse hydrogeological settings. These impacts are often compounded by increasing groundwater abstraction driven by population growth, agricultural expansion, and urbanisation (Wu et al., 2025) [19].

Climate Controls on Groundwater Recharge

Groundwater recharge occurs when water infiltrates through the soil profile and reaches the saturated zone of an aquifer. Precipitation characteristics, evapotranspiration, soil properties, vegetation cover, land use, topography, and hydrogeological conditions influence recharge rates. Climate change primarily affects groundwater recharge through changes in precipitation and evapotranspiration. Changes in rainfall amount, intensity, frequency, and seasonality influence the quantity of water available for infiltration. Simultaneously, increasing temperatures and atmospheric evaporative demand enhance water losses from soils and vegetation, reducing the proportion of precipitation available for recharge.

Recharge responses to climate change vary considerably among regions. In humid environments, moderate increases in precipitation may enhance groundwater recharge, whereas in arid and semi-arid regions, increasing evapotranspiration often outweighs precipitation gains, resulting in declining recharge rates. Consequently, climate change is expected to produce highly heterogeneous groundwater responses at regional and basin scales (Berghuijs et al., 2024) [20]. Recent global assessments indicate that recharge sensitivity is particularly high in regions characterised by seasonal rainfall patterns and shallow aquifer systems, where small climatic changes can produce substantial alterations in groundwater availability (Berghuijs et al., 2024; Davamani et al., 2024) [20, 21].

Groundwater Storage Decline and Aquifer Depletion

The increasing depletion is one of the most concerning consequences of climate change on groundwater storage. Groundwater storage reflects the cumulative balance between recharge and abstraction over time. When groundwater withdrawals exceed recharge, aquifer storage declines, resulting in falling water tables and reduced water availability.

Climate change accelerates groundwater depletion through several mechanisms. Rising temperatures increase evapotranspiration and irrigation demand, thereby increasing groundwater withdrawals. Simultaneously, declining recharge and more frequent droughts reduce aquifer replenishment. The combined effect often leads to persistent groundwater deficits and declining groundwater resilience (Liu et al., 2025) [22]. Long-term groundwater depletion can have serious socioeconomic and environmental consequences, including reduced agricultural productivity, increased pumping costs, land subsidence, deterioration of water quality, and diminished drought-buffering capacity.

Groundwater–Surface Water Interactions

Groundwater and surface water are interconnected components of the hydrologic cycle. Groundwater contributes to streamflow through baseflow discharge, while rivers, lakes, and wetlands may provide recharge to adjacent aquifers. Climate-induced changes in groundwater storage, therefore, have important implications for surface water systems. Declining groundwater levels reduce baseflow contributions to

rivers, leading to lower dry-season flows and increased vulnerability to hydrological drought. Many perennial rivers are increasingly experiencing intermittent flow conditions as groundwater storage declines. Such changes affect aquatic ecosystems, water supply reliability, and environmental flow requirements. Recent studies suggest that groundwater-fed streams are among the most vulnerable freshwater ecosystems under climate change because reductions in groundwater discharge can substantially alter water temperature, dissolved oxygen concentrations, and habitat conditions (Egidio et al., 2024; Li et al., 2024) [23, 22]. These impacts may be particularly severe in regions already experiencing groundwater overexploitation (Alao et al., 2024; Biswas & Tortajada, 2024) [24, 25]. Climate change is therefore transforming not only groundwater systems themselves but also the broader hydrological networks that depend upon groundwater support.

Coastal Aquifers and Saltwater Intrusion

Coastal groundwater systems face additional challenges associated with climate change. Rising sea levels, combined with declining freshwater recharge and excessive groundwater pumping, increase the risk of saltwater intrusion into coastal aquifers. Saltwater intrusion occurs when saline groundwater migrates into freshwater aquifers. This process reduces groundwater quality and limits freshwater availability for domestic, agricultural, and industrial uses. Low-lying coastal regions and small island aquifers are particularly vulnerable.

Recent assessments indicate that many coastal aquifers are already experiencing salinisation due to combined climate and anthropogenic pressures (Richardson et al., 2024) [26]. Future sea-level rise is expected to further exacerbate these impacts, particularly in densely populated coastal regions of South Asia, Southeast Asia, and the Mediterranean Basin (Monioudi et al., 2025) [27]. Protecting coastal aquifers will require integrated management strategies that address both groundwater abstraction and climate adaptation.

Implications for Water Security

Groundwater is widely regarded as the most reliable freshwater source during droughts and periods of climatic uncertainty. However, climate change is gradually eroding this buffering capacity by reducing recharge, increasing abstraction pressures, and altering groundwater–surface water interactions. The future sustainability of groundwater resources will depend on the balance between climatic pressures and management interventions. Failure to address climate-induced groundwater vulnerabilities may compromise water security, agricultural productivity, ecosystem health, and socioeconomic development across many regions of the world. Therefore, understanding the impacts of climate change on groundwater recharge and storage is essential for developing integrated water resource management strategies that sustain freshwater supplies under increasingly uncertain hydroclimatic conditions. Figure 2 summarizes these interconnected pathways and highlights the cascading impacts of climate change across major hydrological components.

CLIMATE CHANGE AND HYDROCLIMATIC EXTREMES

Hydroclimatic extremes, including floods, droughts, heatwaves, and compound events, are among the most significant consequences of climate change for the hydrologic cycle. While gradual changes in precipitation, evapotranspiration, runoff, and groundwater recharge influence long-term water availability, extreme events often produce the most severe environmental, economic, and societal impacts. Recent observations indicate that climate change is increasing not only the frequency and intensity of individual extreme events but also the occurrence of complex and interacting hazards that challenge conventional water management approaches.

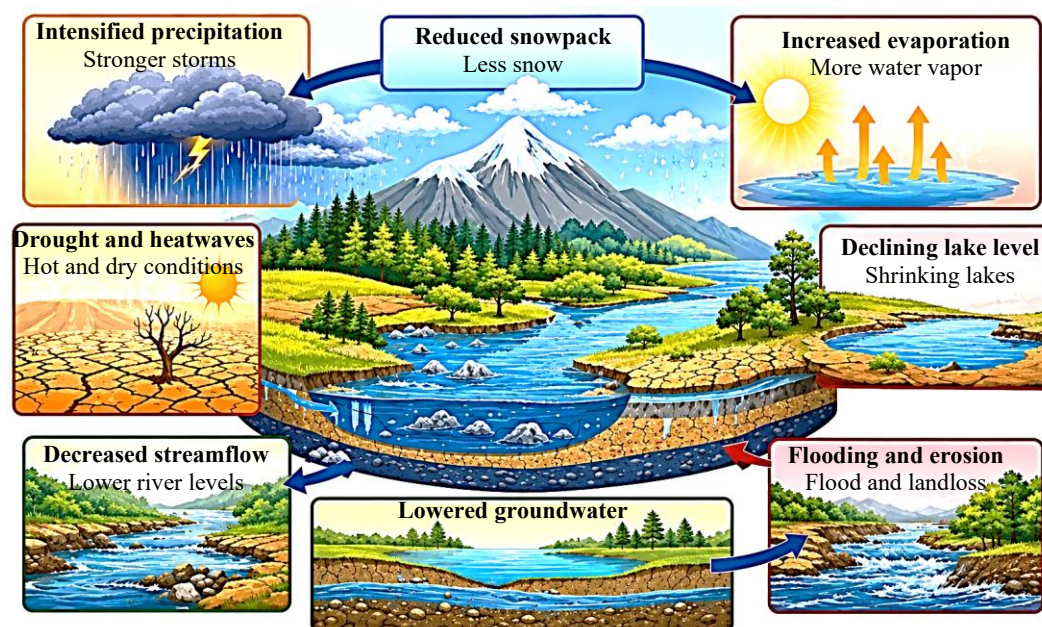


Figure 2. Climate change impacts on hydrological components.

The intensification of the hydrologic cycle under global warming has enhanced atmospheric moisture transport, increased precipitation extremes, elevated evaporative demand, and altered land–atmosphere feedback mechanisms. Consequently, many regions are experiencing unprecedented hydrological variability characterised by severe floods, prolonged droughts, and rapid transitions between contrasting hydrological states. These changes are reshaping watershed resilience and increasing risks to water security, food production, infrastructure, and ecosystem health (Na et al., 2025; Thomas et al., 2025) [28, 29].

Climate Change and Flood Extremes

Floods and droughts are among the most significant hydrological consequences of climate change, posing substantial risks to water security, ecosystems, infrastructure, and human livelihoods. Rising atmospheric temperatures increase the atmosphere's moisture-holding capacity, leading to more intense precipitation events and a higher likelihood of extreme rainfall. Consequently, many regions have experienced increases in flood frequency, magnitude, and associated damages over recent decades. Enhanced moisture transport through atmospheric rivers, intensified monsoon systems, and stronger convective storms contribute to severe flooding. At the same time, land-use changes, urbanisation, and watershed degradation often amplify these impacts by reducing infiltration and increasing surface runoff (Dharmarathne et al., 2024) [30]. Flood responses vary geographically, with high-latitude regions experiencing greater flood risks due to increased precipitation and earlier snowmelt, tropical regions facing more intense rainfall and cyclone-induced flooding, and mountainous areas becoming increasingly vulnerable to glacier lake outburst floods (GLOFs), accelerated snowmelt, and landslide-related flooding. The consequences include loss of life, damage to infrastructure, disruption of water supply systems, agricultural losses, and deterioration of water quality, prompting a shift toward integrated risk-based and nature-based flood management strategies.

In contrast, droughts develop gradually through prolonged imbalances between water availability and atmospheric water demand and are increasingly intensified by climate change. Rising temperatures increase evapotranspiration rates, accelerating moisture loss from soils, vegetation, and water bodies, and thereby exacerbating drought severity even in regions with limited changes in precipitation. Climate change influences multiple forms of drought, including meteorological drought caused by prolonged precipitation

deficits; agricultural drought resulting from insufficient soil moisture for crop growth; hydrological drought characterised by reduced streamflow, reservoir storage, and groundwater availability; and socioeconomic drought, which occurs when water shortages disrupt economic activities and societal well-being. Increasing atmospheric evaporative demand has emerged as a major driver of drought intensification worldwide, contributing to more frequent and severe drought events in regions such as the Mediterranean Basin, western North America, southern Africa, and South Asia (Vicente-Serrano et al., 2022) [12]. Together, the increasing frequency of both floods and droughts highlights the growing hydroclimatic variability associated with climate change and underscores the need for adaptive, resilient water resources management strategies.

Heatwaves and Hydrological Responses

Heatwaves are increasingly recognised as critical components of hydroclimatic change because of their strong interactions with water resources. Rising temperatures increase evapotranspiration, reduce soil moisture, accelerate reservoir evaporation, and intensify drought conditions. The combination of heatwaves and droughts often produces disproportionately severe impacts compared to either hazard occurring independently. For example, prolonged heatwaves can rapidly deplete soil moisture reserves, reduce crop yields, increase wildfire risk, and exacerbate water shortages. Similarly, drought conditions can amplify heatwave intensity by reducing evaporative cooling from soils and vegetation.

Modern studies suggest that the frequency, duration, and intensity of heatwaves have increased significantly since the late twentieth century and are projected to continue increasing under all future emission scenarios. These trends have important implications for water demand, ecosystem functioning, and hydrological resilience (Papadopoulos et al., 2024) [31].

Compound Hydroclimatic Events

An emerging area of climate research focuses on compound events, which occur when multiple climatic or hydrological hazards interact simultaneously or sequentially to produce impacts that are greater than those associated with individual events. Examples include heatwave–drought events, drought–wildfire interactions, extreme rainfall following prolonged drought, storm surges coinciding with river flooding, and heatwave-induced water quality degradation. Climate change is increasing the likelihood and severity of such events by enhancing atmospheric variability and strengthening interactions among hydrological, ecological, and climatic processes.

Recent global assessments indicate that compound hydroclimatic events are increasing faster than individual extremes, posing significant challenges for risk assessment, disaster preparedness, infrastructure planning, and water resources management. Understanding and predicting these complex interactions are therefore critical for developing effective adaptation and resilience strategies under future climate change scenarios (Marlier et al., 2025) [32].

Hydroclimatic Whiplash

The hydroclimatic whiplash, characterised by rapid transitions between extremely wet and extremely dry conditions, is one of the most striking manifestations of climate change. Such abrupt shifts have been observed with increasing frequency across North America, Europe, Asia, and Australia. Hydroclimatic whiplash occurs because a warmer atmosphere simultaneously enhances both precipitation extremes and evaporative demand. As a result, regions may experience severe drought followed by catastrophic flooding within the same season or year.

Current evidence indicates that hydroclimatic whiplash events may increase substantially under future warming scenarios, particularly in regions influenced by strong climate oscillations such as the ENSO.

These events challenge traditional water management systems because infrastructure designed for drought mitigation may not be adequate for flood control and vice versa (Mumberg et al., 2024) [33]. The increasing frequency of hydroclimatic whiplash underscores the need for adaptive, flexible water management strategies that can address rapidly changing hydrological conditions.

Implications for Water Security and Watershed Resilience

Hydroclimatic extremes pose significant risks to water security by disrupting both water availability and water quality. Floods can damage water infrastructure, contaminate water supplies, and increase sediment and pollutant transport. Droughts reduce reservoir storage, groundwater recharge, and streamflow, threatening domestic, agricultural, and industrial water supplies. Ecosystems are similarly vulnerable. Extreme events can alter habitat conditions, reduce biodiversity, increase species mortality, and disrupt ecological processes. Freshwater ecosystems are particularly sensitive because they depend directly on hydrological conditions.

Building watershed resilience under climate change requires integrated approaches that combine climate adaptation, ecosystem restoration, sustainable groundwater management, flood-risk reduction, and improved hydrological forecasting. Nature-based solutions such as wetland restoration, floodplain reconnection, afforestation, and managed aquifer recharge are increasingly recognised as effective measures for mitigating hydroclimatic risks.

These findings demonstrate that climate change is intensifying hydroclimatic extremes through complex interactions among atmospheric, terrestrial, and hydrological processes. The increasing frequency of floods, droughts, heatwaves, compound events, and hydroclimatic whiplash underscores the urgent need for adaptive water management strategies to address a more variable and uncertain hydrological future.

IMPACTS OF CLIMATE CHANGE ON WATER QUALITY AND AQUATIC ECOSYSTEMS

Climate change affects not only the quantity and distribution of water resources but also their quality and ecological integrity. Alterations in temperature, precipitation patterns, runoff processes, streamflow regimes, groundwater dynamics, and hydroclimatic extremes directly influence physical, chemical, and biological characteristics of aquatic environments. Rivers, lakes, reservoirs, wetlands, estuaries, and coastal ecosystems are increasingly experiencing changes in water temperature, dissolved oxygen concentrations, nutrient cycling, sediment transport, and biological productivity. These changes have profound implications for freshwater biodiversity, ecosystem services, drinking water security, and environmental sustainability. Growing evidence suggests that climate change acts as a "threat multiplier" by exacerbating existing anthropogenic pressures such as pollution, land-use change, eutrophication, habitat fragmentation, and the overexploitation of water resources. Consequently, aquatic ecosystems are becoming increasingly vulnerable to ecological degradation under future climate scenarios (Schuster et al., 2026) [34].

Rising Water Temperatures

Water temperature is one of the most important environmental variables governing the functioning of aquatic ecosystems. Increasing air temperatures associated with climate change are causing widespread warming of rivers, lakes, reservoirs, and coastal waters. Recent global assessments indicate that freshwater ecosystems are warming at rates often exceeding those of the atmosphere, due to reduced streamflow, longer water residence times, and altered thermal regimes. Elevated water temperatures influence numerous ecological and biogeochemical processes, including metabolic rates, nutrient cycling, oxygen solubility, and species distribution patterns.

Thermal alterations can significantly affect aquatic organisms by modifying growth rates, reproductive success, migration patterns, and habitat suitability. Cold-water species such as salmonids, trout, and certain

macroinvertebrates are particularly vulnerable because they depend on specific thermal conditions for survival. As water temperatures continue to rise, many species are expected to shift their geographical ranges, experience population declines, or face local extinction risks (Saima et al., 2026) [35]. Furthermore, higher water temperatures often accelerate microbial activity and organic matter decomposition, increasing oxygen demand and altering ecosystem metabolism.

Dissolved Oxygen Dynamics

Dissolved oxygen (DO) is a critical indicator of aquatic ecosystem health. Climate change influences DO concentrations through multiple mechanisms, including increasing water temperatures, changing streamflow conditions, enhanced biological activity, and altered nutrient loading. Warmer water has a lower capacity to retain DO, reducing oxygen availability for aquatic organisms. Simultaneously, elevated temperatures accelerate microbial respiration and organic matter decomposition, further increasing oxygen consumption. Reduced streamflow during drought periods can exacerbate oxygen depletion by decreasing reaeration and increasing pollutant concentrations.

DO concentrations have declined substantially across freshwater and marine ecosystems, a phenomenon increasingly referred to as aquatic deoxygenation. Low-oxygen conditions can impair fish growth, alter community composition, reduce biodiversity, and increase mortality of sensitive species (Mahaffey et al., 2023) [36]. Deoxygenation is particularly problematic in reservoirs, lakes, and slow-moving river systems where stratification limits oxygen exchange between surface and bottom waters.

Nutrient Cycling and Eutrophication

Climate change is altering nutrient transport and biogeochemical cycling within watersheds and aquatic ecosystems. Changes in precipitation intensity, runoff generation, soil erosion, and hydrological connectivity influence the movement of nitrogen, phosphorus, and organic matter from terrestrial environments to water bodies.

Intense rainfall events often increase nutrient export from agricultural and urban areas, thereby elevating nutrient loading into rivers, lakes, and reservoirs. Increased nutrient availability promotes eutrophication, characterised by excessive algal growth, oxygen depletion, and ecological imbalance. At the same time, prolonged droughts can concentrate nutrients within water bodies due to reduced dilution capacity. The alternation between drought and flood conditions may further accelerate nutrient mobilisation and ecosystem instability.

Climate change is increasingly recognised as a key driver of eutrophication, even in aquatic systems where nutrient management programs have substantially reduced external nutrient loading. This highlights the importance of incorporating climate–water quality interactions into watershed management strategies (Dory et al., 2024) [37].

Harmful Algal Blooms

Harmful algal blooms (HABs) are among the most visible manifestations of climate-induced deterioration in water quality. Rising temperatures, nutrient enrichment, altered hydrological regimes, and increased water residence times create favourable conditions for bloom formation and persistence in both freshwater and coastal ecosystems. Cyanobacterial blooms are of particular concern because many species produce toxins that pose significant risks to human health, aquatic organisms, and drinking water supplies.

Climate change promotes the occurrence and proliferation of HABs through multiple mechanisms, including increased water temperatures, enhanced thermal stratification, elevated nutrient loading from

runoff, reduced flushing rates, and more frequent drought conditions that prolong water residence times. These factors collectively enhance algal growth and increase the likelihood of bloom development. Recent observations indicate a substantial rise in the frequency, duration, intensity, and geographic extent of harmful algal blooms worldwide, affecting rivers, lakes, reservoirs, estuaries, and coastal waters. Under future warming scenarios, these trends are expected to intensify further, posing significant challenges for water treatment, ecosystem management, public health protection, and the sustainable use of freshwater resources (Wang et al., 2025) [18].

ADAPTATION AND MITIGATION STRATEGIES FOR CLIMATE-RESILIENT WATER RESOURCES MANAGEMENT

The growing impacts of climate change on the hydrologic cycle necessitate a transition from reactive water management to proactive, climate-resilient strategies. Increasing hydroclimatic variability, intensifying floods and droughts, declining groundwater reserves, deteriorating water quality, and ecosystem degradation are challenging traditional water resources planning frameworks developed under the assumption of climatic stationarity. Consequently, adaptation and mitigation measures are increasingly being integrated into water resources management to enhance resilience, reduce vulnerabilities, and ensure sustainable water security under future climate conditions.

Climate-resilient water management seeks to improve the capacity of natural and human systems to anticipate, absorb, recover from, and adapt to climate-induced disturbances while maintaining essential ecosystem functions and water services. Effective adaptation requires an integrated approach that combines engineering interventions, ecosystem-based solutions, technological innovations, institutional reforms, and stakeholder participation.

Integrated Water Resources Management

Integrated Water Resources Management (IWRM) remains one of the most widely recognised frameworks for addressing complex water challenges under climate change. IWRM promotes the coordinated development and management of water, land, and related resources to maximise economic and social welfare while ensuring the long-term sustainability of ecosystems. The increasing impacts of climate change have further reinforced the importance of IWRM, as hydrological responses and water-related challenges frequently transcend administrative, political, and sectoral boundaries. Effective climate adaptation, therefore, requires integrated management of surface water, groundwater, ecosystems, agriculture, urban infrastructure, and energy systems.

Core adaptation principles within the IWRM framework include basin-scale planning and management, conjunctive use of surface water and groundwater resources, ecosystem-based water management, stakeholder participation and collaborative governance, adaptive decision-making under uncertainty, and the incorporation of climate projections into planning and policy processes. By fostering coordination among sectors and stakeholders, IWRM enhances water systems' capacity to respond to climatic variability and extreme events. Recent assessments indicate that river basin organisations implementing IWRM principles demonstrate greater resilience to climate-related water stress and achieve more sustainable water management outcomes than fragmented, sector-specific management approaches (Duda & Hirji, 2025) [38].

Nature-Based Solutions for Climate Adaptation

Nature-Based Solutions (NbS) are increasingly recognised as cost-effective and sustainable approaches for enhancing hydrological resilience under climate change. By leveraging natural processes and ecosystem functions, NbS address water-related challenges while simultaneously delivering environmental, social, and economic benefits. Key adaptation measures include watershed restoration through reforestation,

afforestation, and rehabilitation activities that improve infiltration, reduce surface runoff, enhance groundwater recharge, and stabilise hydrological regimes.

Wetland conservation and restoration play a critical role in storing floodwaters, improving water quality, supporting biodiversity, and maintaining environmental flows during dry periods. Similarly, reconnecting rivers to their floodplains increases natural flood storage capacity, reduces downstream flood peaks, and enhances ecosystem productivity. In urban environments, green infrastructure such as urban green spaces, permeable pavements, bioswales, rain gardens, and green roofs promotes infiltration, mitigates stormwater runoff, and reduces flood risks. Recent studies indicate that NbS can provide climate adaptation benefits comparable to conventional engineering infrastructure while generating additional co-benefits, including biodiversity conservation, carbon sequestration, improved ecosystem services, and enhanced community resilience (Ghaedi et al., 2026) [39].

Climate-Smart Agriculture and Water Management

Agriculture accounts for approximately 70% of global freshwater withdrawals and is highly vulnerable to climate-induced changes in water availability. Climate-smart agriculture (CSA) seeks to enhance agricultural productivity, strengthen resilience to climate variability, and reduce environmental impacts through sustainable water management practices. Key CSA strategies include precision irrigation technologies, drip and sprinkler irrigation systems, drought-tolerant crop varieties, soil moisture conservation measures, rainwater harvesting, conservation agriculture, and crop diversification. These approaches improve water-use efficiency, reduce irrigation demands, and enhance the capacity of agricultural systems to cope with droughts and changing rainfall patterns. Improved irrigation efficiency can substantially reduce freshwater withdrawals while maintaining, or even increasing, crop productivity.

Furthermore, integrating climate forecasting into irrigation scheduling has been shown to improve water-use efficiency, optimise irrigation timing, and strengthen drought preparedness. Climate-smart agricultural practices also support groundwater sustainability by minimising excessive groundwater extraction, promoting soil-water retention, and enhancing opportunities for groundwater recharge, thereby contributing to long-term water and food security under changing climatic conditions.

Future Pathways Toward Water Resilience

Future water management systems must move beyond conventional engineering-based approaches and adopt integrated, adaptive, and ecosystem-based strategies to address the growing challenges posed by climate change effectively. Building climate resilience will increasingly depend on the successful integration of scientific knowledge, technological innovation, stakeholder participation, and sustainable governance frameworks. Key priorities for future adaptation include strengthening climate-informed water planning, expanding the implementation of nature-based solutions, improving groundwater sustainability, enhancing hydroclimatic forecasting and early warning systems, integrating advanced technologies such as artificial intelligence and digital twins into water management, protecting aquatic ecosystems, and building institutional and community resilience.

These measures will help improve the capacity of water systems to anticipate, withstand, and recover from climate-related stresses and extreme events. The transition toward climate-resilient water resources management represents one of the most critical challenges of the twenty-first century. It will require coordinated efforts across scientific disciplines, economic sectors, governance institutions, and local communities to ensure sustainable water security under increasingly uncertain hydroclimatic conditions.

RESEARCH GAPS AND FUTURE DIRECTIONS

Despite significant advances in climate science, hydrological modelling, remote sensing, and water resources management, substantial uncertainties remain regarding the magnitude, timing, and spatial

variability of climate change impacts on the hydrologic cycle. The complexity of interactions among atmospheric processes, terrestrial ecosystems, groundwater systems, cryospheric dynamics, and human activities continues to challenge accurate prediction of future hydrological responses. Uncertainties arise from differences among climate models, greenhouse gas emission scenarios, downscaling techniques, hydrological model parameterization, land-use changes, and human water management interventions. Precipitation remains particularly difficult to project at regional and local scales, propagating uncertainties throughout assessments of runoff, groundwater recharge, droughts, and floods.

Furthermore, groundwater–climate interactions remain insufficiently understood due to limited monitoring networks, long response times, and complex hydrogeological conditions. Critical questions persist regarding future recharge dynamics, groundwater–surface water interactions, and the long-term resilience of aquifer systems. Research on compound and cascading hydroclimatic events, such as drought–wildfire sequences, heatwave–drought interactions, and flood events following prolonged drought, is also limited despite their increasing occurrence and potentially severe impacts. These challenges are compounded by data scarcity, fragmented monitoring networks, inadequate water-quality observations, and restricted access to hydrological datasets, particularly in developing regions and transboundary river basins. Strengthening integrated monitoring systems that combine field observations, satellite remote sensing, citizen science, and automated sensor networks is therefore essential for improving climate impact assessments and reducing uncertainty.

Future hydrological research must adopt interdisciplinary and integrated approaches that explicitly account for human–water interactions, ecosystem processes, and emerging technological innovations. Human activities, including reservoir operations, groundwater abstraction, irrigation, urbanization, and land-use change, increasingly influence hydrological systems and should be more effectively represented within climate impact assessments. Advances in artificial intelligence, machine learning, big-data analytics, and digital twin technologies offer unprecedented opportunities for improving flood forecasting, drought monitoring, streamflow simulation, groundwater assessment, infrastructure optimization, and climate adaptation planning.

However, challenges related to model interpretability, uncertainty quantification, and integration with physical processes remain unresolved. In parallel, greater attention is needed to understand climate-induced changes in water quality, freshwater biodiversity, ecosystem services, ecological flow requirements, and climate-sensitive biomonitoring indicators. Future research should prioritize multi-scale climate–hydrology interactions, coupled human–natural systems, climate-resilient infrastructure, nature-based adaptation strategies, integrated water quantity–quality assessments, sustainable groundwater management, ecosystem resilience, and decision-support systems for adaptive water governance. Addressing these priorities through collaborative efforts across hydrology, climate science, ecology, engineering, economics, and social sciences will be critical for improving understanding of climate-induced hydrological change and supporting the development of resilient and sustainable water management systems in an increasingly uncertain climatic future.

CONCLUSIONS

Climate change is fundamentally altering the hydrologic cycle by modifying precipitation patterns, evapotranspiration, soil moisture, runoff, streamflow, groundwater recharge, and water quality. Rising temperatures and increasing atmospheric moisture are intensifying hydroclimatic extremes, including floods, droughts, heatwaves, and compound events, thereby increasing uncertainty in water availability and ecosystem sustainability. These changes threaten water security, agricultural productivity, aquatic ecosystems, and socioeconomic development worldwide. Groundwater depletion, declining water quality,

and ecological degradation further compound these challenges. To address these impacts, climate-resilient water management strategies, such as IWRM, nature-based solutions, climate-smart agriculture, sustainable groundwater management, and advanced technologies, including remote sensing, artificial intelligence, and digital twins, are increasingly essential. Although significant progress has been made in understanding climate–hydrology interactions, uncertainties remain regarding regional responses and future extremes. Continued interdisciplinary research, adaptive governance, and climate-informed water management are critical for enhancing resilience and ensuring sustainable freshwater resources in the face of future climate change.

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