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MICRO-CREDENTIAL

CLIMATE CHANGE FOR SUSTAINABLE LAND MANAGEMENT IN CENTRAL ASIA

4.- Water, Cryosphere and Climate in Central Asia

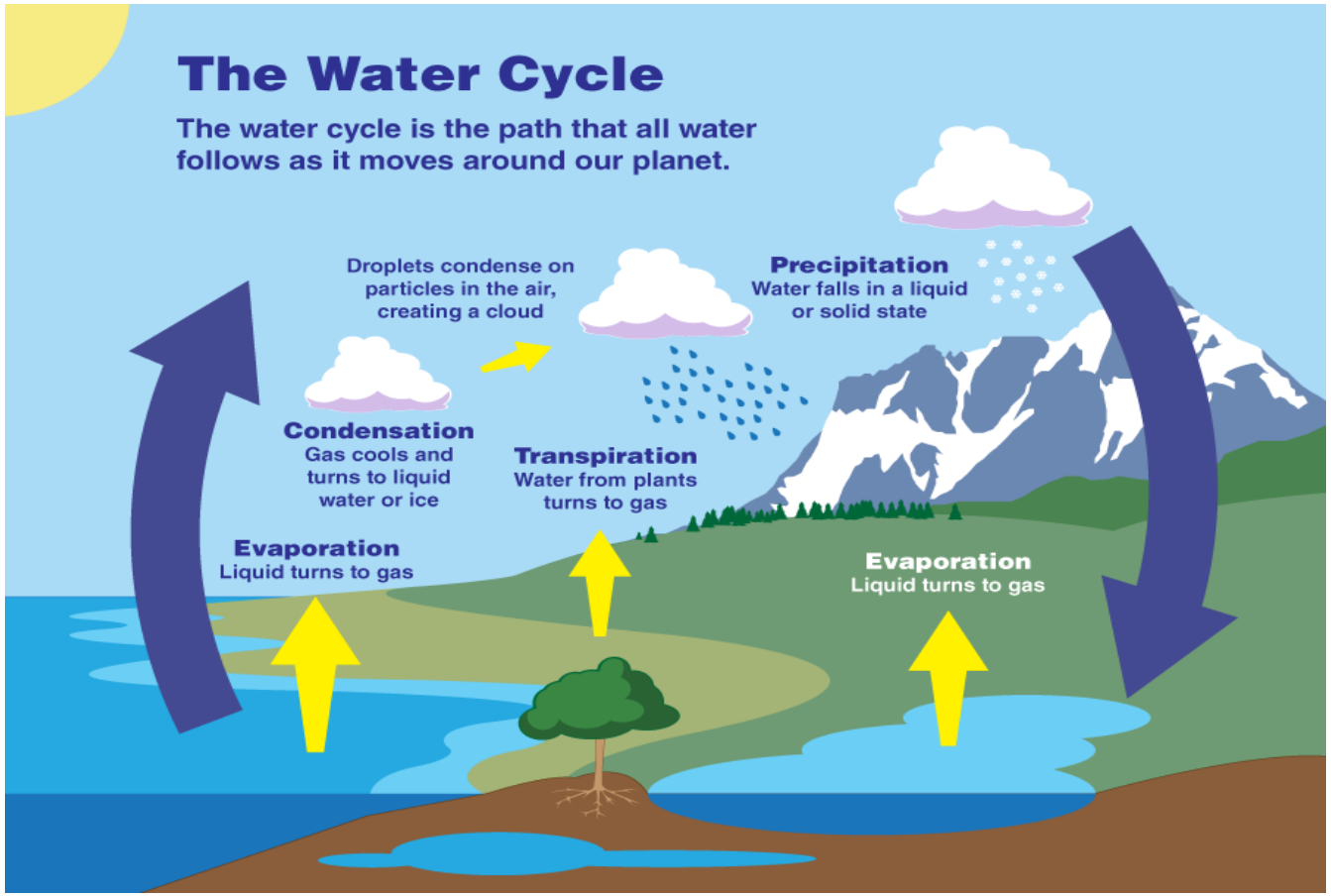
The Global Water Cycle and Climate

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Introduction

The **global water cycle**, also known as the Hydrologic Cycle, is a fundamental Earth system process that describes the continuous movement of water within the atmosphere, hydrosphere, lithosphere, and biosphere. This cycle is tightly interconnected with the Climate System, influencing weather patterns, temperature regulation, and ecosystem dynamics.

Understanding the water cycle is essential for interpreting climate variability, predicting extreme weather events, and assessing the impacts of human activity on Earth's systems.



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Components of the Global Water Cycle

The hydrologic cycle consists of several key processes:

a. Evaporation and Transpiration

Evaporation: The transformation of liquid water into vapor, primarily from oceans, lakes, and rivers.

Transpiration: The release of water vapor from plants.

Together, these processes are often referred to as **evapotranspiration**.

Solar energy drives evaporation, making it a crucial link between the water cycle and climate.

b. Condensation

Water vapor cools and condenses into tiny droplets, forming clouds. This process is central to cloud formation and atmospheric dynamics.

c. Precipitation

Water returns to Earth's surface as rain, snow, sleet, or hail. Precipitation patterns are highly dependent on atmospheric circulation and temperature.

d. Infiltration and Runoff

Infiltration: Water seeps into the soil and replenishes groundwater.

Runoff: Water flows over land into rivers, lakes, and oceans.

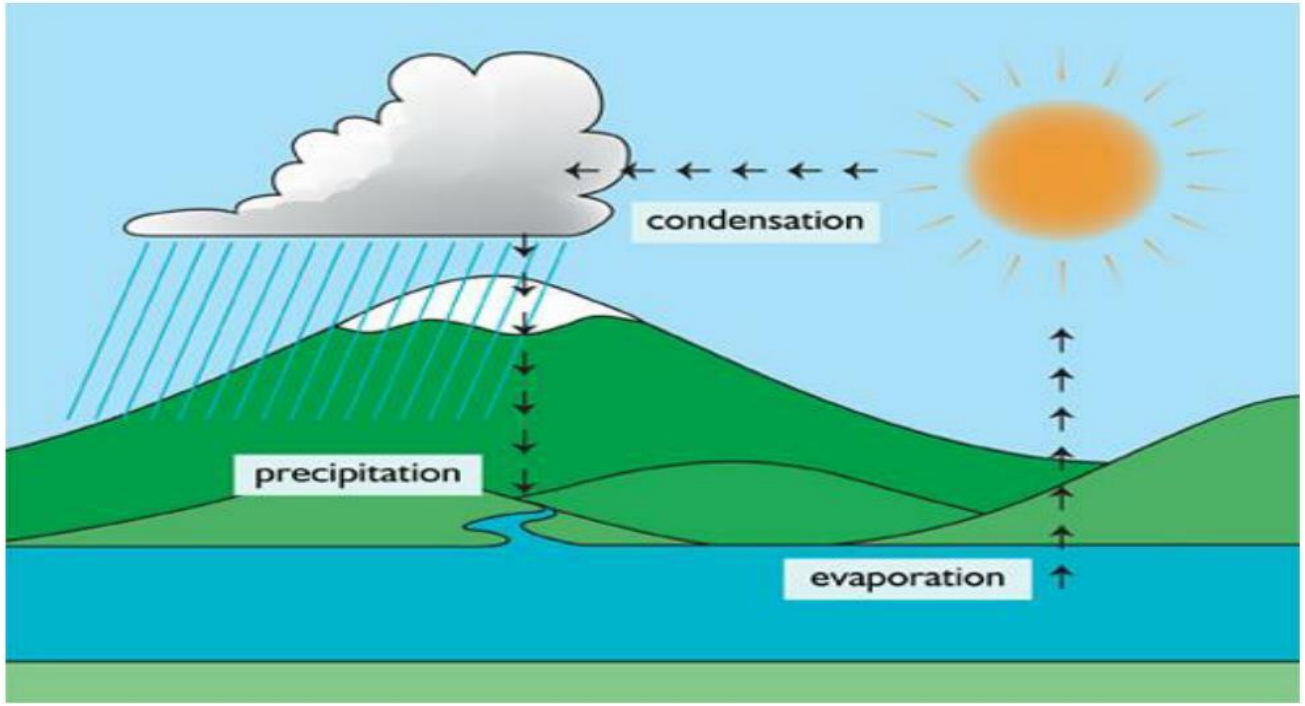
These processes determine freshwater availability and influence erosion and landscape formation.

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Energy Balance and the Water Cycle

- The water cycle is driven by Earth's energy balance, primarily governed by incoming solar radiation and outgoing terrestrial radiation.
- Evaporation absorbs heat (latent heat flux), cooling the surface.
- Condensation releases heat into the atmosphere, influencing atmospheric circulation.
- This exchange of energy links the water cycle directly to the Earth's Energy Budget and plays a major role in regulating global temperatures.

The sun's energy fuels the water cycle and impacts different aspects of the water cycle.



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Interaction Between the Water Cycle and Climate

a. Atmospheric Circulation

Large-scale wind systems redistribute heat and moisture around the globe. For example:

Tropical regions experience high evaporation and precipitation.

Polar regions have low evaporation and limited precipitation.

b. Climate Zones

The distribution of precipitation helps define climate zones such as:

Tropical (wet)

Arid (dry)

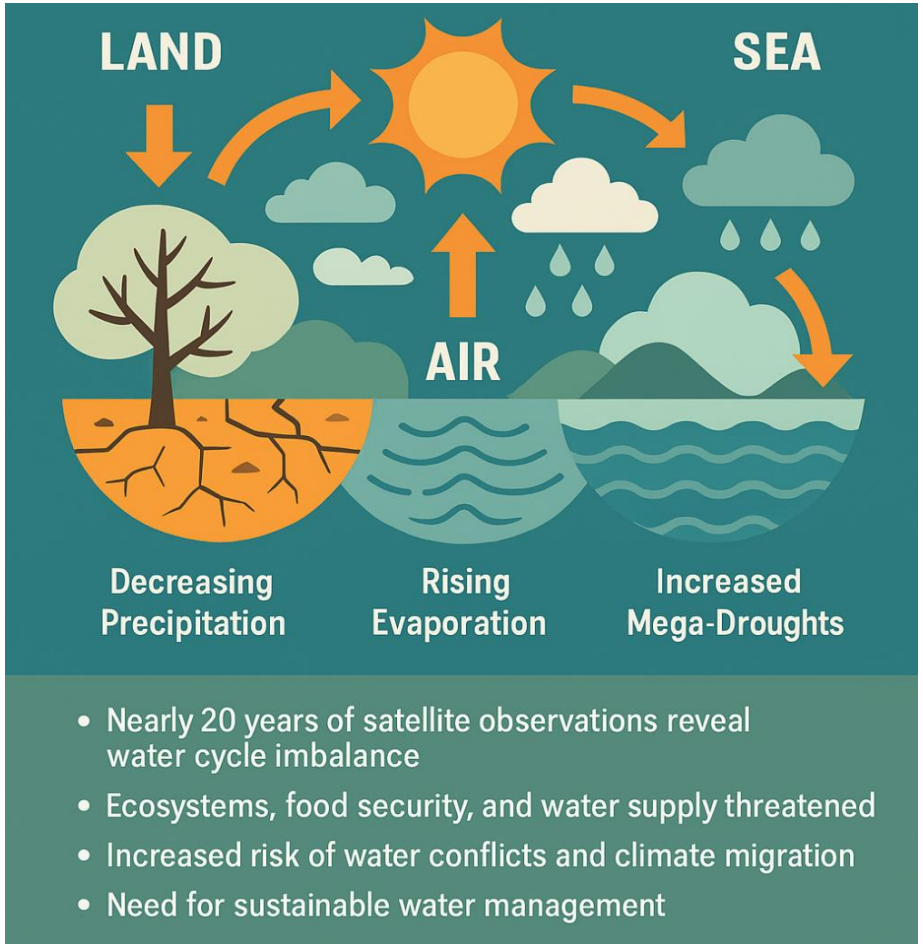
Temperate (moderate)

c. Feedback Mechanisms

The water cycle participates in several climate feedback loops:

Water vapor feedback: Water vapor is a powerful greenhouse gas. Increased temperatures lead to more evaporation, which increases atmospheric water vapor and enhances warming.

Cloud feedback: Clouds can either cool (by reflecting sunlight) or warm (by trapping heat), depending on their type and altitude.



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Human Impacts on the Water Cycle

Human activities are increasingly altering the natural water cycle:

a. Land Use Changes

Deforestation reduces transpiration.
Urbanization increases runoff and reduces infiltration.

b. Water Extraction

Overuse of groundwater leads to depletion of aquifers.

c. Pollution

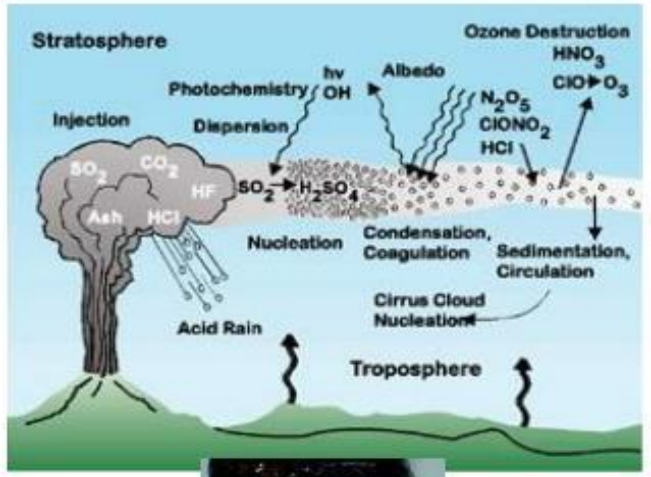
Contaminates freshwater systems, affecting ecosystems and human health.

d. Climate Change

Anthropogenic climate change intensifies the water cycle:
Increased evaporation rates
More intense precipitation events
Longer and more severe droughts

How Humans affect the Water Cycle

- Human Use of Water:
  - Agriculture
  - Dams and Deforestation
  - Urbanization (Living in Cities)
  - Overuse of Aquifers
    - Saltwater Intrusion (ocean)
    - Subsidence (lead to collapse)
- **Clean Water supply**
  - 1 billion people (16%) do **not** have any access to clean water.
  - Can cause outbreaks of **disease**
    - Examples: cholera, hepatitis, mosquito breeding, etc.
- **Acid Rain (in combination with Nx and Sx)**
  - Hurts plants, animals and buildings



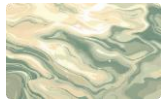


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The Unseen Engine of Our Planet

Water circulates continuously around the planet through a set of linked processes: evaporation from oceans and inland waters, transpiration from plants, condensation into clouds, precipitation as rain or snow, and collection in rivers, lakes, glaciers and groundwater. This global water cycle is the fundamental engine that sustains life, moderates temperatures, sculpts landscapes and supplies the freshwater we rely on. Despite the vast amount of water on Earth, only about **1%** of it is readily available freshwater for ecosystems and people — a finite, precious resource whose distribution and timing determine agricultural yields, energy production, biodiversity and human wellbeing.



Evaporation

Solar energy converts surface water into vapour from oceans, lakes and soil, driving the upward leg of the cycle.



Transpiration

Plants release water vapour from leaves — collectively a major source of atmospheric moisture, especially over vegetated land.



Condensation & Cloud Formation

Water vapour cools and condenses on aerosols to form clouds, the reservoirs that eventually return water to the surface.



Precipitation & Collection

Rain, snow and other forms of precipitation replenish rivers, groundwater and glaciers, completing the circuit that sustains ecosystems and societies.

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The Global Water Cycle: A System Under Pressure

The water cycle is not static — it responds to energy imbalances, land-use change and atmospheric composition. Over the last century, human activities (notably greenhouse gas emissions, deforestation, irrigation and urbanisation) have altered the energy and moisture budgets of the Earth system. These changes affect where and when moisture is stored and released: shifting patterns of precipitation, changing seasonality, reduced snowpacks, altered river regimes, and stressed groundwater reserves. The consequences are widespread: altered flood risk, drought frequency, water availability for cities and agriculture, and impacts on ecosystems that rely on precise hydration cycles.

Energy Forcing

Warming increases the atmosphere's capacity to hold moisture, changing evaporation and condensation balances.

Land-Use Change

Agriculture, urban growth and deforestation alter transpiration and runoff patterns, affecting local and regional cycles.

Water Management

Dams, extraction and diversion change natural collection and recharge, decoupling humans from the historic cycle.

Why This Matters

Small shifts in timing or quantity of water can cascade into crop failures, reduced hydropower generation, increased conflict over scarce resources and loss of biodiversity. Integrated assessment — linking climate, hydrology, ecology and human systems — is essential to manage risk and build resilience.

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A Warming World, A Changing Cycle

As global temperatures rise, key physical drivers of the water cycle accelerate: warmer air holds more water vapour (Clausius–Clapeyron relation), increasing potential evaporation and atmospheric moisture. This extra moisture can intensify rainfall events, while simultaneously increasing evaporative demand over land, exacerbating soil moisture deficits. The net result is a more energetic, less predictable system — with consequences for storm intensity, drought onset and the partitioning of water between surface runoff and groundwater recharge.

Increased Evaporation

Higher temperatures raise the rate of evaporation from oceans and land, mobilising more moisture into the atmosphere.

Storm Intensification

Greater atmospheric moisture fuels short-duration, high-intensity storms that produce large rainfall totals in brief periods.

Exacerbated Droughts

Despite heavier rainfall in some places, stronger evaporation and reduced soil moisture persistence can deepen drought conditions.

Observational analyses and climate model ensembles indicate a global-scale acceleration of the water cycle linked to anthropogenic forcing. However, the local outcomes depend strongly on atmospheric circulation, topography, land cover and seasonal timing.

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Beyond "Wetter Gets Wetter, Drier Gets Drier"

The shorthand "wetter gets wetter, drier gets drier" (WWDD) captures a first-order expectation but misses important nuances. Real-world responses are governed by: (1) seasonality — some regions may see wetter winters and drier summers; (2) circulation changes — shifting storm tracks and monsoon behaviour can redistribute moisture; and (3) component-specific responses — precipitation intensity, frequency, and evapotranspiration can change independently. Consequently, policy and adaptation must be tailored to regional dynamics rather than rely on overly simple global slogans.

Local Seasonality Matters

Agricultural calendars, snowmelt timing and reservoir operations are sensitive to when precipitation falls, not just how much.

Circulation Shifts

Jet stream changes, monsoon shifts and alterations in atmospheric rivers can move moisture away from historical recipients.

Component-Specific Trends

Intense rainfall events may increase even where total annual precipitation declines — harming infiltration and increasing runoff.

For decision-makers, this translates to the need for granular, seasonally-resolved climate-hydrology projections and localised risk assessments that incorporate both extremes and changes in water storage.

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The Shocking Revelation: Permanent Decline

Recent analyses synthesising decades of observations — including satellite gravimetry (GRACE), long-term streamflow records, groundwater monitoring and land-surface models — point to an alarming signal: a substantial, widespread decline in terrestrial water storage. Published in Science (March 2025), this work documents persistent negative trends in groundwater and river baseflow in many regions, suggesting more than transient variability; instead, a long-term shift in how and where freshwater is stored on land.

1 Evidence Base

Multi-decade satellite gravimetry shows declining mass over major aquifers and river basins, corroborated by in-situ wells.

2 Implications

Reduced storage means less buffering capacity against drought and altered seasonality of water availability for agriculture and cities.

3 Drivers

Combined influences: climate-driven evapotranspiration increases, unsustainable groundwater extraction, and changing precipitation patterns.

This "permanent" decline is not uniform: some basins show recovery where recharge increases or management improves, but the overall global signal is cause for urgent reassessment of water stewardship, recharge enhancement and demand management strategies.

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Intensifying Imbalances: Dry Regions Lead the Way

Counterintuitively, many dry regions are experiencing relatively larger increases in precipitation intensity than traditionally wet areas. However, increased evapotranspiration — driven by higher temperature and greater atmospheric demand — can more than offset these precipitation gains. The result: short-duration extreme rainfall events that yield high runoff and limited infiltration, while net water availability for ecosystems and human use can decline.

Step 1 — Moisture Surge

Warming mobilises moisture into the atmosphere; storms become capable of delivering large instantaneous rainfall totals.

Step 2 — Elevated Evapotranspiration

Higher temperatures increase evaporation and plant water loss, drawing down soil moisture following storms.

Step 3 — Reduced Recharge

Fast runoff from intense storms limits groundwater recharge, reducing longer-term storage despite higher peak flows.

Practically, this pattern raises flood risk and undermines sustainable water supply: reservoirs may see more variable inflows, groundwater recharge can decline, and agricultural reliability suffers — especially in water-scarce regions that lack buffering capacity.

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Human Fingerprints on the Water Cycle

Multiple lines of evidence show human influence on the hydrological cycle. Anthropogenic greenhouse gas emissions alter radiative balance, increasing atmospheric moisture and reorganising circulation cells. Land-use changes — deforestation, irrigation expansion, urban sealing — modify evapotranspiration rates and runoff pathways. Direct water management (pumping, reservoirs, diversions) changes the distribution of terrestrial storage. Together, these activities create detectable signals that distinguish recent changes from natural variability.

Climate Forcing

Greenhouse gases raise temperatures, altering evaporation, snowmelt timing and atmospheric moisture content.

Land Cover Change

Removing vegetation lowers transpiration in some regions while urbanisation increases runoff and reduces infiltration.

Direct Extraction

Unsustainable groundwater pumping depletes aquifers and severs the link between surface water and long-term storage.

Attribution studies combining observations and models can separate human fingerprints from natural drivers, enabling targeted mitigation and adaptation actions: emissions reductions, land management reforms, improved irrigation efficiency, and groundwater regulation.

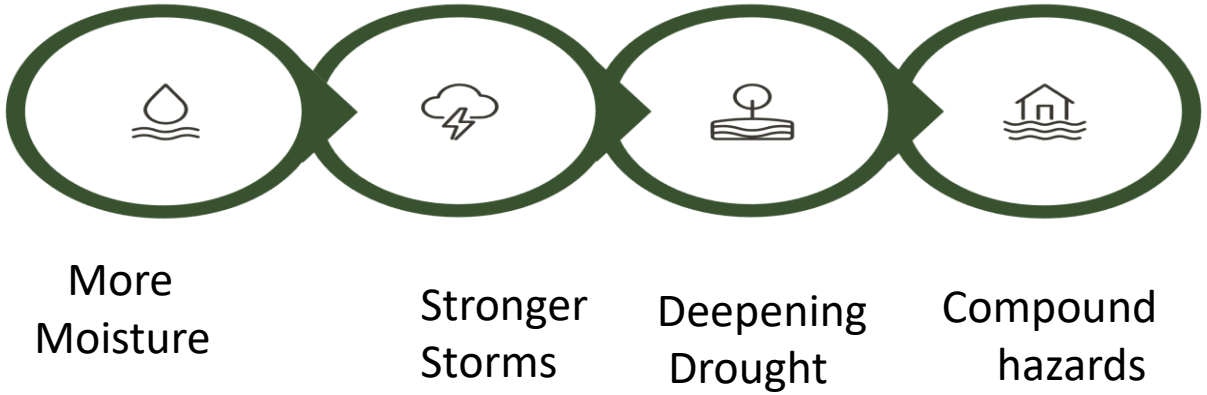
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The Extremes of a Changing Water Cycle



A more energetic water cycle amplifies extremes at both ends: heavier, often more localised precipitation events producing floods and flash-floods; and enhanced evaporative demand producing longer, deeper droughts and heatwaves. These extremes interact with one another: drought-stressed soils and vegetation can increase wildfire risk, while post-fire landscapes are more prone to erosion and debris flows during intense rainfall. Coastal regions face compound risks from sea-level rise feeding into storm surges alongside shifting precipitation.

This cascade highlights why adaptation must be systemic: infrastructure design, emergency planning, ecosystem management and land-use policy must anticipate correlated, cascading risks rather than treating floods or droughts in isolation.



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The Stakes: Water Resource Crises

Intensification and redistribution of the water cycle increase the likelihood and severity of water resource crises. Sectors affected include: agriculture (crop yields and irrigation reliability), energy (hydropower and cooling water for thermal plants), public water supply (reservoir levels, groundwater), and ecosystems (wetland drying, species stress). Vulnerable communities — particularly in arid and low-income regions — face the highest risks because they lack capacity for rapid adaptation or alternative water sources.

1%	Science 2025	Multiple
Freshwater available	Key study	Sectors affected
Of global water accessible for human use, roughly 1% is easily reachable freshwater, placing a premium on sustainable management.	March 2025 Science paper documents irreversible declines in terrestrial storage across many basins — a global signalling event for policy.	Agriculture, energy, cities and ecosystems — requiring cross-sectoral planning and investment for resilience.

Addressing these stakes requires integrated water resource management, investments in monitoring (satellites, in-situ networks), demand-side efficiency, conjunctive use strategies (surface + groundwater) and governance that can respond flexibly to shifting seasonal patterns.

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Conclusion

- The global water cycle is a dynamic and interconnected system that plays a central role in Earth's climate. Its processes regulate temperature, distribute energy, and sustain life. As climate change accelerates, disruptions to the water cycle are becoming more pronounced, making it essential to study and manage water resources sustainably.
- A comprehensive understanding of the hydrologic cycle not only enhances our knowledge of Earth systems but also equips us to address pressing environmental challenges in the 21st century.

Climate Change and the Intensification of the Water Cycle

A warming atmosphere can hold more moisture, leading to:
Heavier rainfall events
Increased flooding risk
Enhanced drought in dry regions
This phenomenon is often described as the "intensification" or "acceleration" of the hydrologic cycle.

Extreme Events and Variability

Changes in the water cycle contribute to extreme weather events:
Hurricanes and typhoons gain energy from warm ocean water.
Floods result from intense precipitation.
Droughts occur when evaporation exceeds precipitation over long periods.
Understanding these processes is crucial for climate adaptation and risk management.

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