ERASMUS-EDU-2023-CBHE
Project number: 101129032

Duration: 36 months
(01/01/2024 – 31/12/2026)

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CLIMATE CHANGE FOR SUSTAINABLE LAND MANAGEMENT IN CENTRAL ASIA

4.- Water, Cryosphere and Climate in Central Asia

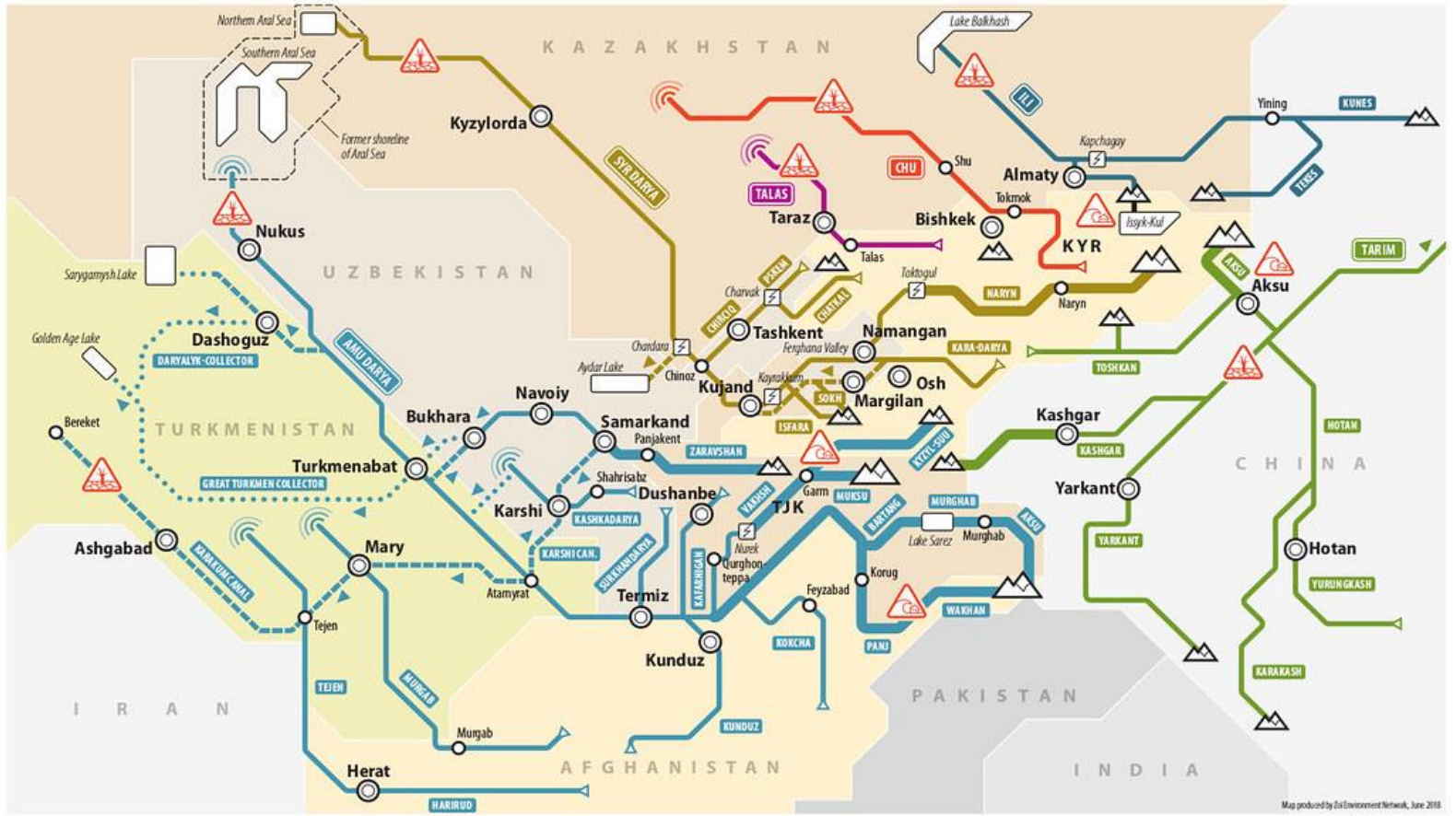
Glaciers, Snowpack and River Regimes in Central Asia

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Introduction

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- Central Asia is a predominantly arid and semi-arid region where water resources are critically dependent on high-mountain cryospheric systems. The major mountain ranges-Tien Shan and Pamir Mountains-act as “water towers,” storing winter precipitation in the form of snow and ice and releasing it gradually through melt processes. This system sustains river flow across downstream countries such as Kazakhstan, Uzbekistan, Kyrgyzstan, and Tajikistan.
- Understanding glaciers, seasonal snowpack, and river regimes is essential for water management, agriculture, hydropower, and climate adaptation in the region.



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Glaciers in Central Asia

a. Distribution and Characteristics

Central Asia hosts thousands of glaciers, primarily located in high-altitude regions:
The Tien Shan contains one of the largest glacier systems outside the polar regions.
The Pamir Mountains include extensive valley glaciers and ice caps.
Glaciers act as long-term water storage, accumulating snow in winter and releasing meltwater during warmer months.

b. Glacier Mass Balance

The health of glaciers is determined by mass balance, the difference between accumulation (snowfall) and ablation (melting and sublimation).
Positive balance → glacier growth
Negative balance → glacier retreat
In recent decades, most Central Asian glaciers have experienced negative mass balance due to rising temperatures.

c. Climate Sensitivity

Glaciers are highly sensitive to climate change:
Temperature increases accelerate melting.
Changes in precipitation affect accumulation.
This makes them key indicators of regional climate trends.

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Snowpack Dynamics

a. Seasonal Snow Cover

Snowpack refers to the accumulation of snow during winter months. In Central Asia:

Snow accumulates at high elevations.

Spring and early summer melting provide critical water input.

b. Snow Water Equivalent (SWE)

A key metric is **Snow Water Equivalent (SWE)**—the amount of water contained within the snowpack. SWE determines how much runoff will be generated during melt season.

c. Timing of Melt

The timing of snowmelt strongly influences river flow:

Early melt → earlier peak discharge

Late melt → prolonged water availability

Temperature fluctuations and solar radiation control melt rates.

Major River Systems

Central Asia's major rivers originate in glacier- and snow-fed mountains:

a. Amu Darya

Originates in the Pamirs

Historically one of the largest rivers in the region

Critical for irrigation in downstream areas

b. Syr Darya

Originates in the Tien Shan

Flows through multiple countries

Heavily regulated for agriculture and hydropower

These rivers historically fed the Aral Sea, which has dramatically shrunk due to water diversion.

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River Regimes in Central Asia

A river regime describes the seasonal variation in river discharge.

a. Nival Regime (Snow-fed)

Dominated by snowmelt

Peak flows occur in spring

b. Glacio-nival Regime (Mixed glacier and snow)

Common in high mountain basins

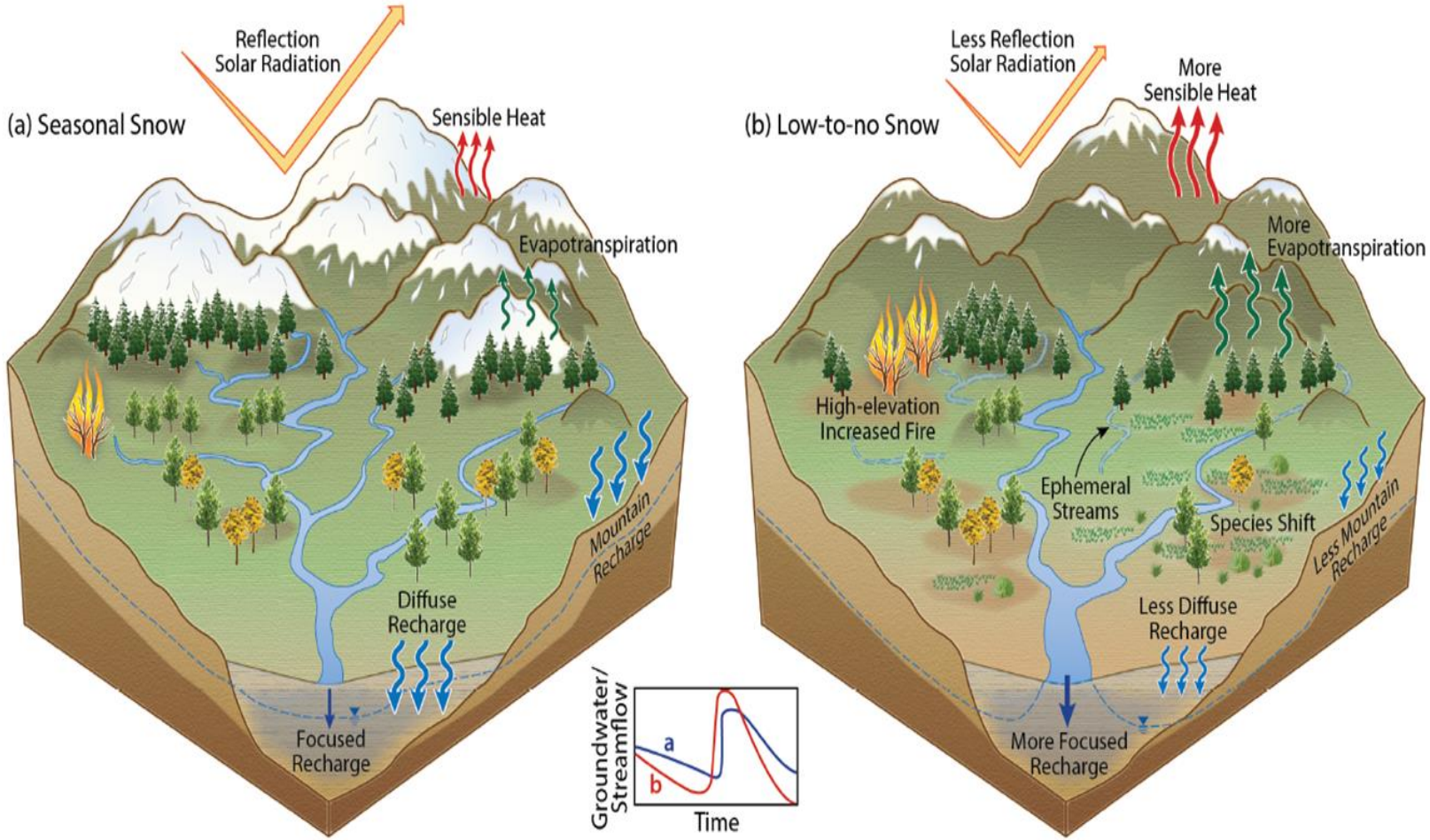
Peak flows in late spring and summer due to combined snow and glacier melt

c. Glacial Regime

Strongly influenced by glacier melt

Peak discharge in summer

Most Central Asian rivers exhibit glacio-nival regimes, making them highly sensitive to temperature changes.



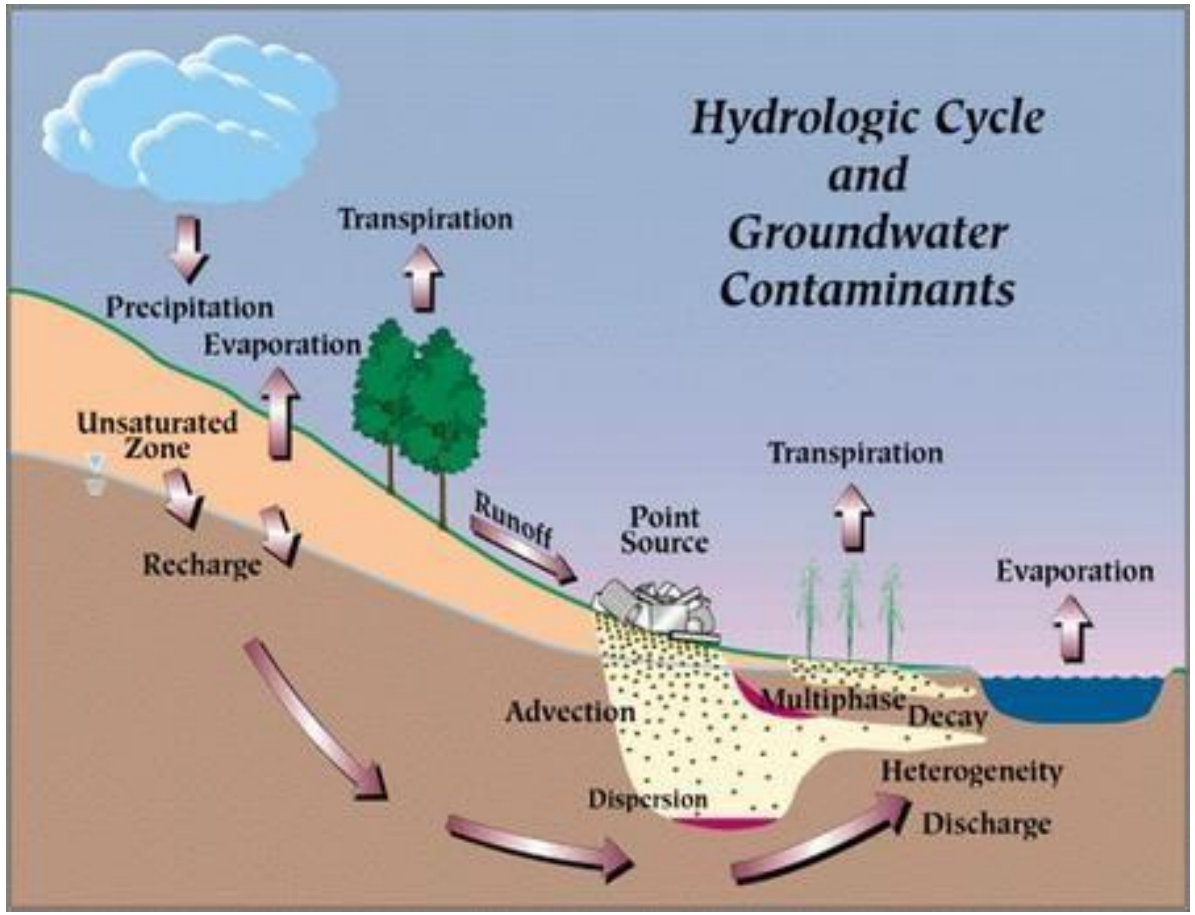
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Hydrological Importance

a. Agriculture
Irrigation systems in downstream countries rely heavily on meltwater: Cotton and wheat production depend on stable river flows.
b. Hydropower
Mountainous countries like Kyrgyzstan and Tajikistan depend on river discharge for electricity generation.
c. Water Security
Seasonal and interannual variability in water supply creates challenges for regional cooperation and resource allocation.

Climate Change Impacts
a. Glacier Retreat
Accelerated melting reduces long-term water storage.
Initial increase in runoff (“peak water”) followed by decline.
b. Changes in Snowpack
Reduced snow accumulation at lower elevations.
Earlier snowmelt shifts river peak flows.
c. Altered River Regimes
Increased variability in discharge.
Greater risk of floods and droughts.



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Environmental and Socioeconomic Consequences

a. The Aral Sea Crisis

Diversion of water from the Amu Darya and Syr Darya has led to:

Severe shrinkage of the sea

Ecosystem collapse

Health and economic impacts

b. Transboundary Water Conflicts

Shared rivers create tensions between upstream and downstream countries:

Upstream: prioritize hydropower

Downstream: prioritize irrigation

c. Natural Hazards

Glacial lake outburst floods (GLOFs)

Landslides and debris flows

Monitoring and Research

a. Remote Sensing

Satellite data is widely used to monitor:

Glacier extent

Snow cover

River discharge patterns

b. Field Measurements

Mass balance studies

Snow surveys

Hydrological gauging stations

c. Modeling

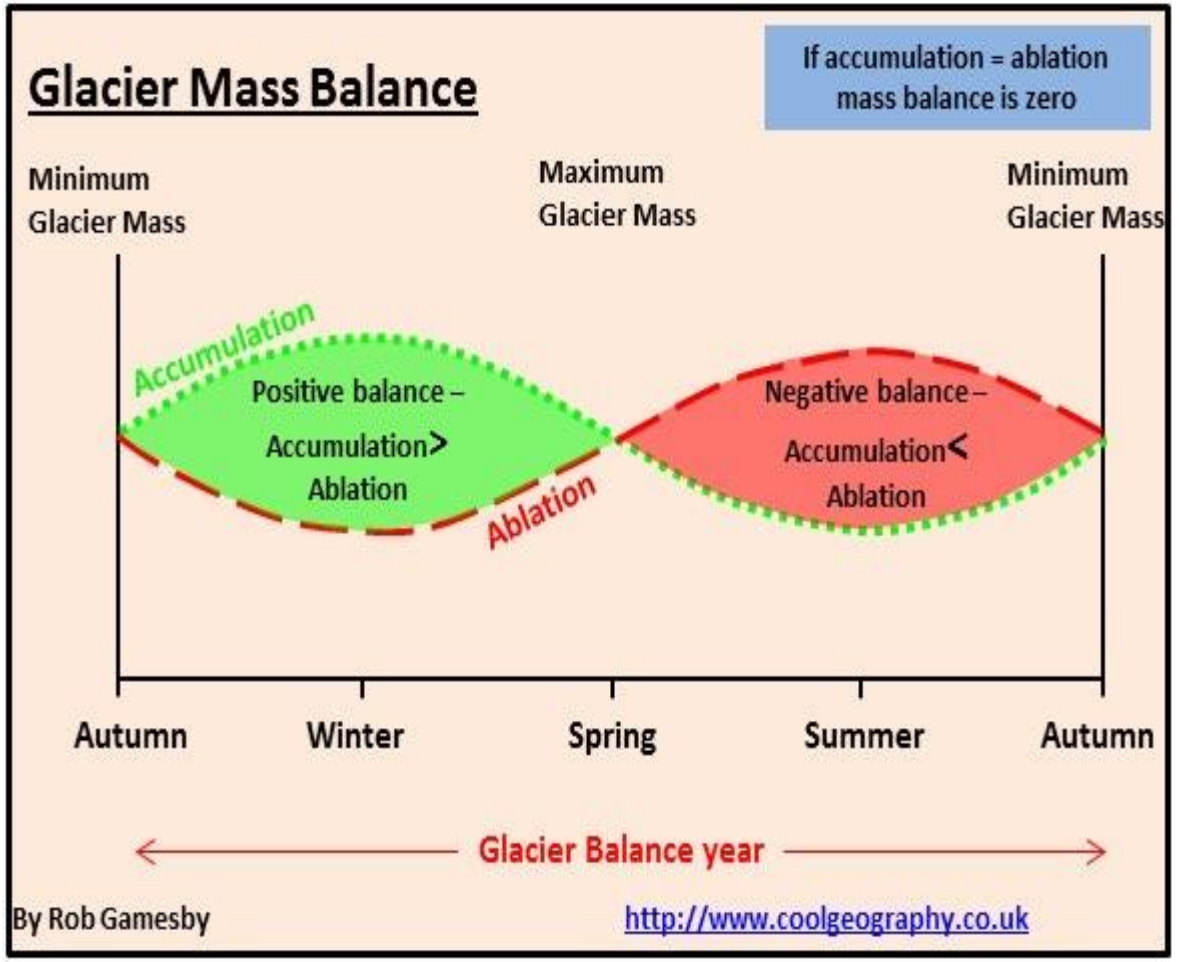
Hydrological and climate models help predict future changes in water availability.

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Glacier mass balance, snowfall patterns

More than one billion people across High Mountain Asia depend directly or indirectly on seasonal snow and glacier melt. These high-elevation cryospheric systems act as natural reservoirs—storing winter precipitation as snow and ice, then releasing it through the spring and summer months. The meltwater supports irrigation for staple crops, fuels hydropower stations that stabilise national grids, and supplies municipal and industrial water. Because the timing, volume and temperature of meltwater control agricultural calendars and electricity production, small shifts in cryospheric dynamics cascade into large socioeconomic effects.

In this presentation we examine the physical drivers (glacier mass balance, snowfall patterns), observed changes, implications for river regimes, and practical adaptation responses for water managers, planners and policy makers.



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Central Asia's Water Towers: A Melting Crisis

Glaciers and seasonal snowpack in the Tien Shan, Pamirs, Karakoram and the Hindu Kush form the region's water towers. Collectively they moderate streamflow variability and supply late-summer water when rainfall is scarce. Rising global temperatures have accelerated cryospheric change across these ranges, but the pattern is spatially heterogeneous: some mass-balanced glaciers show temporary stability while many others demonstrate sustained mass loss. The variability complicates regional planning and demands basin-by-basin assessments.

Visible Losses

Field observations and repeat imagery document retreat of many valley glaciers and thinning of ice caps—changes that reduce long-term water storage.

Scientific Monitoring

Ice cores, geodetic surveys and remote sensing (satellite altimetry) provide complementary lines of evidence on mass change and ice dynamics.

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An Urgent Call for Adaptation

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Central Asia faces a dual challenge: a dynamic cryosphere reshaping water availability, and human systems—agriculture, energy, urban water supply—that remain dependent on historical flow regimes. Effective adaptation requires three interlinked strands:

1. Better Data & Modelling

Expand high-elevation monitoring, blend satellite products (MODIS, GRACE, altimetry) with in-situ observations, and develop basin-scale hydrological models that resolve snow, glacier and groundwater interactions to produce actionable forecasts.

2. Infrastructure & Demand Management

Invest in multi-purpose storage (small reservoirs, managed aquifer recharge), modernise irrigation to increase efficiency, and implement water-sensitive crop planning to reduce peak-season demand.

3. Governance & Cooperation

Strengthen transboundary institutions, align allocation with seasonal forecasts, and integrate pollution control with flow management so water quality is preserved during low-flow periods.

These measures, combined with mitigation efforts to limit long-term warming, can reduce the risk of water scarcity and conflict. The region's future depends on proactive policy, sustained investment in science and infrastructure, and inclusive governance that protects vulnerable communities while preserving ecosystem services.

Shrinking Giants: Glacier Retreat in Central Asia

Central Asia contains some of the last relatively intact mountain glaciers outside polar regions. Yet warming-driven mass loss is widespread. Recent studies report mixed trends: a minority of glaciers—often at very high elevations or fed by unique climatic patterns—show stability or slight gains, but the majority record negative mass balances. Negative mass balance means glaciers lose more snow and ice in melt seasons than they re-accumulate in winter, producing long-term shrinkage and reduced contribution to late-season baseflow.

Key Drivers

- Atmospheric warming and altered precipitation patterns
- Black carbon and dust deposition increasing ice albedo loss
- Topographic factors that control shading and accumulation

Consequences

- Reduced long-term water storage in ice
- Seasonal flow amplification followed by decline (peak-water)
- Increased glacial lake formation and downstream flood risk

Understanding regional heterogeneity is critical: blanket statements (all glaciers retreat uniformly) obscure local conditions that determine water availability for communities and agriculture.

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Snowfall Decline: A Growing Concern

Beyond glacier mass, seasonal snowpack is the immediate store that feeds rivers during spring and early summer. Recent observations show declining snowfall and shorter snow-cover duration in several parts of High Mountain Asia—especially in mid-elevation bands that contribute disproportionately to seasonal meltwater. In the Northwestern Pamirs and some headwater basins, station and satellite records indicate fewer snow days and reduced snow-water equivalent (SWE) in critical months.

01

1. Less Winter Accumulation

Warmer winters increase the rain–snow threshold elevation, reducing snowfall accumulation at marginal elevations that historically stored substantial water.

02

2. Shorter Snow Persistence

Earlier onset of melt shortens the duration of snow cover, compressing runoff into earlier months and reducing availability during late summer demand peaks.

03

3. Feedbacks on Glaciers

Reduced seasonal accumulation means less replenishment for glacier mass balance, exacerbating long-term retreat.

These changes undermine both natural buffering capacity and human systems that assume predictable late-season flows for irrigation rotation and hydropower scheduling.

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Impact on River Regimes: The Changing Flow

Hydrological regimes across Central Asia are shifting as the relative contribution of snowmelt versus glacier melt changes. Initially, warming can increase melt rates, producing higher spring flows (a ‘peak-water’ period). Over decades, diminished ice and snowstores lead to lower late-season baseflows. For many western basins, summer dry-season flow has historically depended on gradual melt from seasonal snow and glacier ice; reductions in both sources leave irrigation systems and hydropower vulnerable precisely when demand is highest.

1

Historical

Reliable late-summer flows from persistent snow and glaciers supported multi-crop irrigation cycles.

2

Transitional

Warming increases melt, causing earlier and higher spring floods and larger seasonal variability.

3

Future

After peak-water, multi-year decline in summer flows becomes the norm unless storage and demand measures change.

Water managers must plan for both short-term hydrological extremes (higher floods and drought risk) and long-term reductions in perennial runoff.

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Pollution and River Regimes in Central Asia

River regimes are not only altered by cryospheric change but also by pollution and land-use pressures. Agricultural runoff, industrial discharges and inadequate wastewater treatment combine with altered flow timing to concentrate pollutants during low-flow seasons. Reduced summer flows heighten contaminant concentrations, affecting water quality for irrigation, human consumption and aquatic ecosystems. Thermally altered flows (warmer water from earlier melt) can further reduce dissolved oxygen and stress fisheries.

Industrial Pollutants

Heavy metals and chemical effluents from mining and manufacturing accumulate in sediments and bioaccumulate in food chains.

Agricultural Runoff

Fertilisers and pesticides flow into rivers—nutrient loading causes algal blooms that degrade water quality during warm, low-flow periods.

Sewage & Urban Waste

Insufficient sanitation infrastructure increases pathogen loads, a direct public health hazard when dilution capacity declines.

Tackling pollution must go hand-in-hand with flow management—otherwise adaptations to cryospheric change will be undermined by declining water quality even where quantity is maintained.

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Case Study: The Ferghana Valley

The Ferghana Valley sits at the cross-roads of water demand and supply sensitivity. It relies on transboundary rivers (Syr Darya tributaries) whose headwaters are fed by snow and ice from surrounding ranges. Climate-driven alterations in runoff timing disrupt irrigation schedules for cotton, cereals and vegetables—crops central to regional livelihoods and economies. Reduced late-season flows increase competition between upstream and downstream users and raise the threat of political tensions without cooperative basin governance.

Agriculture at Risk

Irrigation infrastructure built for historical flow regimes struggles with early peak flows and diminished late-summer availability, reducing yields and increasing vulnerability.

Governance Needs

Transboundary collaboration, improved forecasting and flexible allocation rules are essential to reduce conflict risk and support adaptive water sharing.

Investment in conjunctive use—combining surface reservoirs with managed groundwater recharge and modern irrigation—can reduce vulnerability, but requires finance, institutions and trust across borders.

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The Data Tells a Stark Story

Remote sensing and in-situ observations provide critical evidence of cryospheric change. MODIS satellite analyses indicate that, on average, snow cover persists for roughly 102 days in headwater basins of many Central Asian rivers. Yet this average masks troubling negative trends: the number of snow-cover days is declining most rapidly in elevation bands that historically supplied summer melt.

Quantitative Observations

- MODIS-derived snow duration: mean ~102 days in headwaters
- Significant year-to-year variability linked to large-scale circulation (e.g., ENSO, NAO)
- Negative trends concentrated where agricultural demand is highest

Basin Examples

- Syr Darya headwaters: notable reductions in snow days affecting summer flow reliability
- Brahmaputra headwaters: decreased snow duration in some sub-basins with implications for downstream seasonality

These datasets underscore the need for improved, long-term monitoring networks, expanded meteorological stations at elevation, and integrated modelling that blends remote sensing with ground truth to inform adaptation.

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The Water Crisis Unfolds: Before and After

Visualising change helps communicate the magnitude and pace of cryospheric loss. Many valleys show a clear ‘before’—large, buffered glacial systems and late-summer flows—and an ‘after’ characterised by reduced glacier extent, newly exposed moraines, more seasonal variability, and, in some places, the formation of unstable glacial lakes. These physical changes translate to social impacts: shortened growing seasons, increased irrigation competition, elevated flood and landslide risk, and threats to rural livelihoods.

Reduced Snow Accumulation

Less winter storage limits seasonal buffering.

Glacier Thinning & Retreat

Long-term reduction in ice-based storage.

Societal Impacts

Water stress, agricultural loss, health risks from concentrated pollution.

Altered River Regimes

Earlier peaks, lower late-season flows, and increased extremes.

Recognising the full sequence—climate driver to societal outcome—enables targeted interventions at every step of the cycle.

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Conclusion

- Glaciers, snowpack, and river regimes form the backbone of Central Asia's water system. Their interactions determine the timing and quantity of water available for ecosystems, agriculture, and human consumption. However, climate change and human activities are placing increasing stress on these systems.
- A comprehensive understanding of cryospheric and hydrological processes is essential for sustainable water management and regional stability in Central Asia.

Adaptation and Management Strategies

a. Integrated Water Resource Management (IWRM)

Coordinated management across sectors and countries.

b. Improved Irrigation Efficiency

Reducing water losses in agriculture.

c. Reservoir Management

Balancing hydropower generation and water supply needs.

d. Climate Adaptation Policies

Developing strategies to cope with variability and uncertainty.

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