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Perspective

Regional cryosphere strategy for the Hindu Kush Himalaya

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Abstract: The Hindu Kush Himalaya (HKH) hosts the largest concentration of glaciers, seasonal snow, and permafrost outside the polar regions. Ongoing climate change has accelerated glacier mass loss, reduced snow cover, degraded permafrost, and altered runoff seasonality. These changes have amplified multi-hazard risks such as glacial lake outburst floods, avalanches, and landslides, with cascading impacts on water, energy, food, ecosystems, and livelihoods. Yet, field monitoring remains sparse, fragmented, and uneven across the region with limited long-term records and minimal data sharing. This perspective presents a Regional Cryosphere Strategy (RCS) for the HKH that responds to these deficits by: (i) consolidating and institutionalising standardised monitoring of glaciers, snow, and permafrost; (ii) building sustained capacity through specialised regional capacity-building activities, fellowships, and shared instrumentation with priority given to a Gender Equality and Social Inclusion (GESI) framework; (iii) establishing a Regional HKH CryoHub to ensure Findable, Accessible, Interoperable, and Reusable (FAIR) and policy-relevant data and knowledge services; and (iv) prioritising operational decision-support services such as the HKH seasonal Snow Watch for water and energy planning, hazard monitoring and early warning systems, and basin-scale assessments that link cryosphere trends to risks for people and infrastructure. This strategy is designed to align HKH observations and services with global initiatives, ensuring that regional data streams inform global assessments while countries can access technical and financial support mechanisms. We argue that a basin-representative, quality-assured, and interoperable cryosphere observation and services system can strengthen regional resilience, reduce risks, and amplify the HKH voice in global climate dialogues.

Keywords: HKH; Cryosphere; Monitoring standardisation; Regional Strategy; CryoHub

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1 Introduction

The cryosphere of the Hindu Kush Himalaya (HKH) is a critical component of regional water, energy, and ecosystems, supporting the livelihoods of more than 270 million mountain people and over two billion people downstream. However, glaciers have undergone rapid mass loss since 2000, with strong regional variability (Hugonnet et al. 2021; Jackson et al. 2023; Azam 2026). Over the past two decades, research in the HKH and across High Mountain Asia (HMA) has significantly advanced understanding of glacier mass loss, seasonal snow variability, the growth of glacial lakes and related hazards, and permafrost extent and changes (Jackson et al. 2023). Hydrological research has also enhanced understanding of how cryosphere change affects runoff seasonality, water availability, and downstream dependence across major river basins (Immerzeel et al. 2020; Azam et al. 2021; Lovell et al. 2026). Despite this progress, rapid cryosphere change is already affecting planning for water security, infrastructure safety, and disaster risk reduction, however, decision-makers still do not have sufficiently consistent, basin-scale evidence for policy (Koziell and Gyamtsho 2023).

Despite this urgent need, cryosphere observations in the HKH remain sparse, fragmented, and unevenly distributed between countries and elevation bands. This misalignment between the pace of cryosphere changes and the maturity of observation systems limits the region's ability to quantify hazards, design adaptation measures, and contribute robust HKH evidence to global assessments. Major knowledge and practice gaps remain, including the lack of long-term basin-representative in-situ observations, particularly for snow and permafrost, limited harmonisation of methods, metadata, and data governance, and weak translation of observations into operational services for water management, hazard preparedness, infrastructure planning, and climate adaptation. These gaps and the rapid pace of cryospheric change provide the primary motivation for a Regional Cryosphere Strategy (RCS) for the HKH. At the same time, it is important to acknowledge that a range of national monitoring programmes, research initiatives, and regional efforts have generated valuable datasets, technical capacity, and institutional experience across different components of the cryosphere. However, these efforts often remain uneven in coverage and are not yet sufficiently harmonised or sustained to support basin-scale assessments and regional decision-making.

In this perspective, we argue that a basin-representative, quality-assured, and interoperable cryosphere observation and services system for the HKH is both feasible and urgently needed, and we present a concrete regional architecture to achieve it. We outline the approach of the RCS, by initiating and institutionalising standardised monitoring of glaciers, snow, and permafrost, ensuring long-term, basin-representative records that are comparable across the HKH. Another key element is the sustained capacity-building programme that includes specialised regional training activities, fellowships, and shared instrumentation, with Gender Equality and Social Inclusion (GESI) as a core design principle. We also introduce the Regional HKH CryoHub as a data and coordination mechanism that convenes national focal points, promotes FAIR and interoperable data practices. Finally, the RCS will support knowledge services and link field observations to policy-relevant products such as seasonal Snow Watch outlooks, hazard intelligence, and basin-scale risk assessments. The priorities underpinning this strategy are therefore not only scientific, but also operational: strengthening long-term basin-representative monitoring, harmonising observation and data protocols, improving governed regional data interoperability, and translating cryosphere knowledge into practical decision-support services. It also reflects on design principles and lessons that could be useful for other mountain regions and global initiatives.

The RCS was developed through a series of consultations with partners and technical workshops with regional member countries (RMCs). The strategy is designed as a major component of ICIMOD's Strategy 2030 and Medium-Term Action Plan V (MTAP V/MTAPVI), encompassing the enhancement and harmonisation of field monitoring and the emerging HKH CryoHub framework. National experts and partner institutions helped set priorities, design choices, and implementation pathways. Fig. 1 provides a spatial overview of the Hindu Kush Himalaya cryosphere, including the distribution of glaciers, seasonal snow cover, and permafrost across major river basins. It also highlights the dominant atmospheric drivers, including westerly disturbances and the South Asian monsoon, which control the regional variability of snow accumulation and melt, forming the basis for basin-scale hydrological processes discussed in this study.

2 Design Logic and Contribution of the Regional Cryosphere Strategy

The RCS is designed to be an institutional and technical framework that brings together observations,

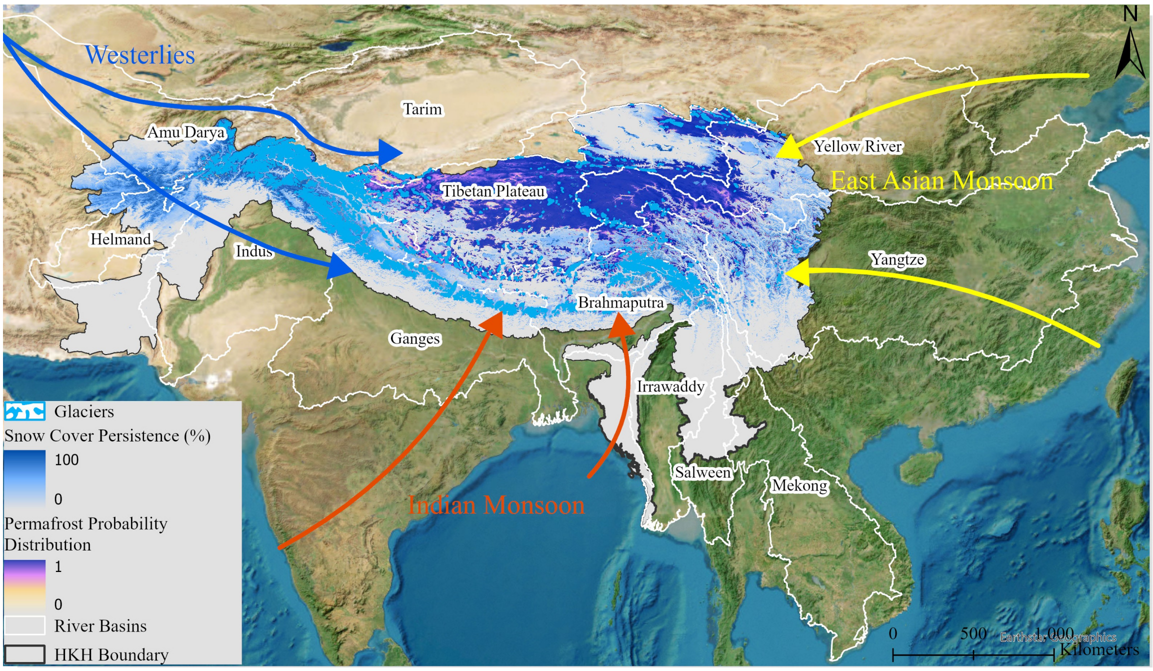

Fig. 1 Glacier extent, snow cover persistence, and permafrost probability distribution across the HKH, overlaid on major river basins, including the dominant atmospheric circulation patterns, westerly disturbances, the Indian and East Asian monsoon systems.

data systems, and decision services into one consistent framework. The framework responds to HKH-specific practical limitations, including a lack of observations across all cryosphere components, uneven national capacities, and diverse institutional mandates. This Perspective contributes a practical design for a regional RCS platform, including the selection of key pillars and expectations for how they will interact over time. It shows how a regional platform like the HKH CryoHub can support the RMCs to work together with coordination, quality assurance, and joint communication without centralising ownership of data or services. It distils useful lessons on how to make cryosphere strategies for data-sparse, hazard-prone mountain regions, which could also be useful for other high-mountain regions. This perspective aims to advance the discussion beyond generic calls for “more monitoring” to a concrete, regionally validated framework that other initiatives can adapt to their specific institutional and climatic contexts.

2.1 Standardised cryosphere monitoring

Under the RCS framework, we have developed a set of operational, standardised cryosphere monitoring guidelines with detailed harmonised approaches for glacier, snow, and permafrost monitoring in the HKH. Drawing on years of field experience and existing best practices, the guidelines translate international standards into HKH-specific, elevation- and context-appropriate procedures for in-situ observations, instrumentation, and long-term monitoring, including benchmark glaciers, distributed snow stations, and near-surface permafrost sensors. These standardised methods and protocols enable consistent monitoring from basin to regional scales. Standardised protocols ensure accuracy, comparability, and long-term utility of observations, and will be accompanied by targeted capacity-building to support adoption across RMCs.

The guidelines are designed to be field-ready and user-friendly, helping partners to collect reliable, comparable in-situ data and apply practical methodologies for assessing the status and evolution of glaciers, snow, and permafrost. While satellite data cover larger areas, field measurements provide critical details that satellite data alone cannot capture. Field measurements allow direct observation of changes in ice, snow, and permafrost, clarify system responses to climate drivers, and generate high-quality reference datasets that are vital for tracking trends and supporting the calibration and validation of satellite- and model-based products as well as improving cryosphere–hydrology models and operational services. Fig. 2 illustrates the scope and content of the standardised cryosphere monitoring guidelines.

2.2 Capacity building and resource sharing

To address critical technical and institutional gaps identified through regional capacity mapping, the strategy prioritises targeted regional capacity building on glaciers, snow, permafrost, and related hazards. Building on ICIMOD's long-standing experience in cryosphere capacity building in glaciers, the permafrost programme was initiated more recently, and regional expertise and observations remain limited outside China. Multiple glacier-monitoring training activities have been conducted in other countries, e.g., India, Nepal, and Pakistan, but comparable efforts and datasets for permafrost are still mostly lacking across the HKH, highlighting the critical gap in structured, region-wide training and comparison.

The capacity-building efforts will combine structured training programmes, collaborative projects, and early-career placements to develop regional expertise. Training activities will be designed to cover the needs of partners and will be tracked through follow-up evaluations. Recognising systemic challenges faced by women and marginalised groups in field-based research such as travel restrictions, safety, and limited opportunities, the cryosphere programme will mainstream GESI through prioritised participation in capacity building events, preference for women and early-career professionals in fellowships and awards, and specialised events for female experts. A practical target is to maintain at least 30% female participation in training activities, progressively moving towards leadership parity.

To support this, the HKH CryoHub secretariat will not only coordinate data management but also help organise capacity-building while promoting global linkages. Citizen-science pilots will be explored to extend observation coverage in accessible areas while maintaining robust QA/QC in all cryosphere products. ICIMOD's open data sharing policy will support broader access, long-term curation, and wider use of cryosphere information for decision-making. However, data contributed by regional partners will be shared according to mutually agreed access arrangements, consistent with national policies, institutional mandates, and data sensitivity.

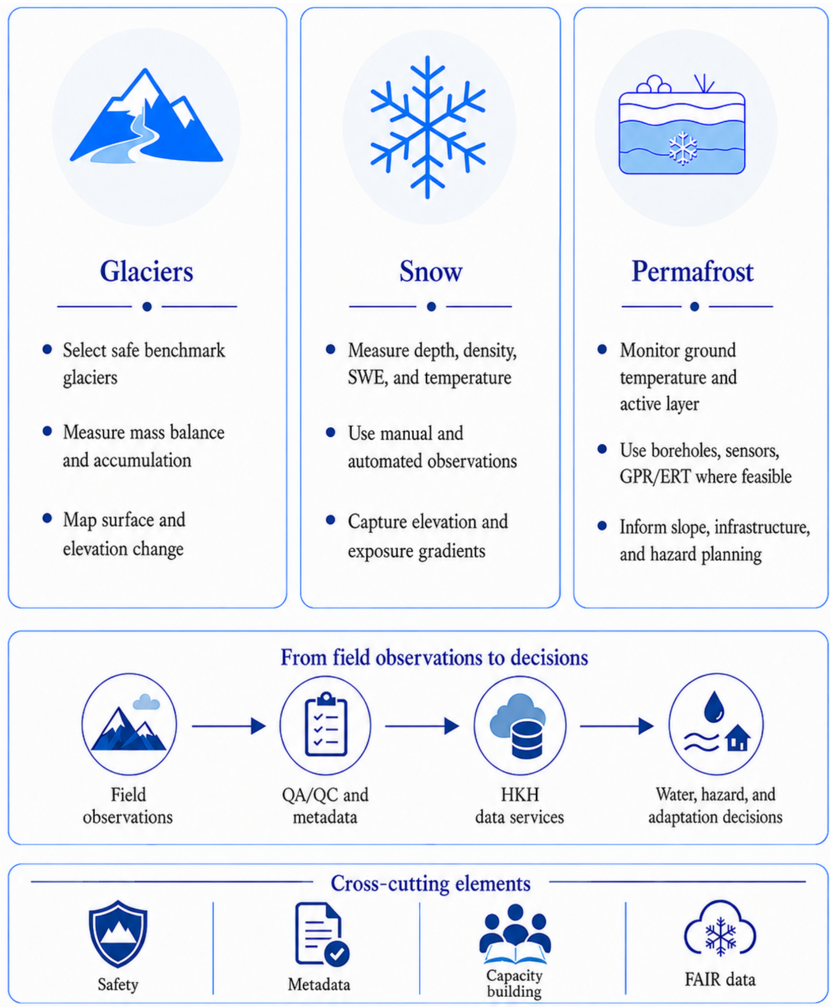

Fig. 2 Scope and structure of standardised cryosphere (glacier, snow, and permafrost) field monitoring guidelines including cross-cutting elements for the HKH.

2.3 HKH CryoHub: regional data, coordination, and policy interface

ICIMOD has developed the HKH CryoHub involving partners from RMCs as members of its Thematic Working Groups (TwGs). An Advisory Working Group (AWG) with members from RMCs and international experts has also been established to strengthen science-policy linkages and guide collective action. ICIMOD hosts the CryoHub secretariat, with TwGs, co-leads, communications, and programme management to coordinate documentation, web presence, and the annual CryoHub Dialogue. The platform will continue and further strengthen ICIMOD's existing regional networking by profiling partners and researchers and highlighting early-career scientists early-career scientists through a "Researcher in the Spotlight" feature. It also disseminates cryosphere data and applications through web-based interactive portals, organises regional events for knowledge sharing and provides regular updates on cryosphere-related activities.

Outreach on cryospheric changes and impacts will ensure coordinated communication by integrating communication tasks into each TwG package, using ICIMOD's existing regional platform (web, social media, policy briefs, and policy dialogues), and coordinating with partners so that the results consistently reach policymakers, practitioners, and communities. The global representation will connect HKH work to initiatives such as GCW, UNFCCC processes, including the Conference of the Parties (COP), and UN-Water platforms, by sharing CryoHub knowledge products, contributing to joint assessments, and co-convening events and technical sessions.

The HKH CryoHub also works through ICIMOD's existing fellowships, internships, and early-career support schemes to prioritise cryosphere topics, through TwG leads and, where resources allow, pilot a small number of targeted mobility opportunities for cross-country fieldwork and data-analysis residencies in a phased and realistic manner. The HKH CryoHub will coordinate the use of cryosphere data from ground observations in collaboration with regional partners. Once partner institutions have the required resources for deploying equipment, a coherent regional approach will be applied for monitoring, including safety and logistics, and, where needed, cross-border agreements. All monitoring activities will follow established measurement standards, drawing on WMO and WGMS standards for data collection, archiving, and submissions. The structure of CryoHub is illustrated in Fig. 3.

2.4 Decision support and services

The RCS implementation aims to translate the scientific and monitoring foundation into practical risk communication, planning, and risk management. Implementation will rely on targeted capacity-building, training national partners to conduct independent field monitoring, analyse and interpret cryosphere data using harmonised protocols, and apply the resulting information in water, energy, infrastructure, and DRR planning. Risk communication will be strengthened through multilingual, locally relevant materials and social media outreach, coordinated with national DRR authorities and cell-broadcast systems, with community feedback loops in selected valleys to refine warning thresholds, triggers, and evacuation plans. GLOF risk management will be advanced through a maintained and regularly updated watchlist of potentially dangerous lakes, building on existing national and global inventories, and on a limited number of pilots for automated lake-level monitoring, high-resolution risk maps with exposure overlays for priority basins, and community co-produced evacuation playbooks with national and local partners. In future, more co-financing will be needed not only for sustainability, but also because cryosphere monitoring and services directly benefit the economy by lowering

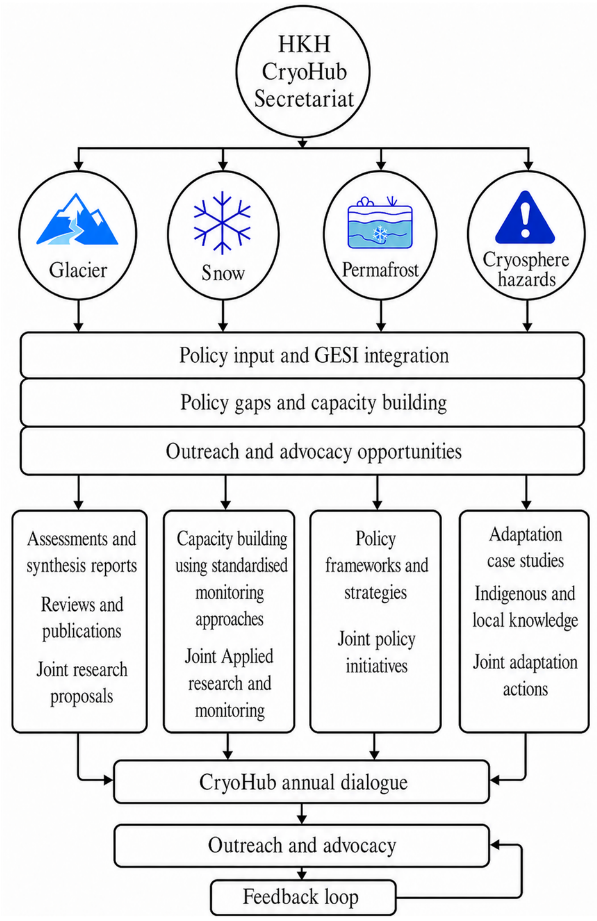

Fig. 3 Structure and key functions of the HKH CryoHub, including thematic working groups and their roles, approaches, and outputs.

disaster losses, improving reservoir and hydropower planning, and supporting smarter investments in climate adaptation.

Governance will be coordinated by the HKH CryoHub secretariat, with strategic guidance from the AWG and technical support from the TwGs. Annual activity reviews will help track progress, while partnership and co-financing opportunities will be explored where appropriate instead of creating new standalone financing mechanisms. To remain relevant, the framework will periodically review and, where appropriate, incorporate advances in Earth observation, AI-enabled forecasting, and probabilistic modelling through targeted, low-regret updates to monitoring and service protocols that are feasible for regional partners to implement. Ultimately, these implementation pathways aim to connect HKH evidence to global systems, embed GESI principles in governance and operations in practical ways, gradually expand community observer networks through existing partner structures, and provide a flexible, evolving model for sustaining cryosphere monitoring, hazard services, and policy linkages in a rapidly changing mountain region.

2.5 Data governance and open science

The RCS prioritises a robust data governance framework built around a Regional Data Portal that follows the standards set by WGMS and WMO Global Terrestrial Networks (GTNs). This framework will support essential metadata requirements, along with version control and QA/QC procedures. While ICIMOD's open data sharing policy provides an important foundation for transparency and wider knowledge use, not all data generated or contributed through regional partners can be fully open. Therefore, formal data-sharing arrangements will be governed through agreements with partner institutions, ensuring appropriate balance between open access principles and the protection of national sovereignty, institutional mandates, and sensitive data. Some data will be subject to time-limited embargoes or confidentiality restrictions.

HKH CryoHub will take the lead on governance, bringing together national focal points, technical experts, and policy representatives, supported by ICIMOD as secretariat. The secretariat will plan and coordinate activities and escalate priorities to ministerial forums. The TwGs will provide updates on progress through the CryoHub. A GESI framework is included in the governance and operational structures. The CryoHub secretariat will proactively identify co-financing opportunities and leverage ICIMOD's ongoing cryosphere activities. This integrated strategy ensures that open science principles, inclusivity, and regional ownership guide the generation, governed sharing, and application of cryosphere knowledge across the HKH.

2.6 Cross-cutting commitments

The RCS incorporates a number of cross-cutting commitments to ensure inclusivity and representativeness, and promote long-term sustainability. The network design and site-selection process will ensure that at least one benchmark glacier is established in each major basin in the HKH region. This approach allows coverage across elevation zones, glacier sizes, aspects, debris cover, and diverse climate conditions, including monsoon, westerly, and continental climates. Sites will be selected based on accessibility, safety, and other factors, following the guidelines set by WGMS/GTN (WGMS 2022). We will also produce consensus estimates of ice thickness, which will be valuable for both network development and field safety.

Partner representation is guided by gender equity and balanced regional participation, while avoiding duplication and overlap in efforts. Capacity will be developed through a series of rotating regional capacity building workshops and in collaboration with recognised universities, focusing on glacier mass balance, snow hydrology, permafrost monitoring, remote sensing, field safety protocols, and data management practices. We will assess equity and participation by considering of gender and social inclusion in cryosphere activities, the number of community observers, and the depth of Indigenous and Local Knowledge (ILK) integration. CryoHub will build inclusive membership and convene an annual HKH CryoHub dialogue to review progress and produce a joint HKH Cryosphere Statement summarising the state of the HKH cryosphere, emerging risks, and priority actions for policy.

2.6.1 From fragmented efforts to harmonised monitoring

Despite the importance of the HKH cryosphere, it is still poorly monitored and under-represented in global knowledge systems. The ongoing glacier mass-balance series (Figure 1 and Table S1 in Azam 2026) and observations of snow and permafrost are sparse (Jackson et al. 2023, Figure 2.8), concentrated in a few easily accessible catchments, and mostly short-term. Methods, metadata, and data policies differ among countries, which limits comparability and basin-scale synthesis. This lack of harmonisation makes it difficult to make reliable, comparable, and actionable assessments at the regional level and weakens the HKH's role in global monitoring frameworks.

The HKH RCS deals with this fragmented landscape through four pillars: standardised cryosphere monitoring; improving regional capacity; the HKH CryoHub as a regional data and coordination hub; and decision-support services that connect observations to risk management and water-energy planning. Together, these pillars make a system that is basin-representative, interoperable, and co-governed, which can help with national planning and global assessments. The RCS is set up in such a way that it can work with other global systems, such as the Global Climate Observing System (GCOS), GTN-G and GTN-P, and the Global Cryosphere Watch from WMO (WMO 2023).

2.6.2 Institutionalising cryosphere monitoring and services

For managing risks associated with rapid cryospheric change, tiered early warning systems that integrate Potentially Dangerous Glacial Lakes (PDGL) watchlists, updates on GLOF events, and exposure overlays provide graded alerting and targeted preparedness. For the water and energy sectors, snow persistence anomalies support pre-monsoon water-availability assessments, the development of resilient reservoir rule curves, and consideration of sediment loads.

The strategy also tackles common weaknesses in regional initiatives such as the knowledge and monitoring of permafrost. Fragmentation is addressed through shared repositories, open APIs/OGC services, and reproducible analytics that make authoritative, "single-source-of-truth" products possible without centralising raw control. Field schools, exchanges, and mentored residencies help retain trained staff. Financial risk is reduced through progressive cost-sharing, while national investment is justified by economic benefits of sustained cryosphere services, including better water allocation, reduced infrastructure disruption, and lower losses from poorly anticipated hazards.

There are still some limitations, such as gaps in observability in remote valleys, debris-covered glaciers, and permafrost corridors where logistics make it difficult to carry out boreholes and geophysical monitoring. Improved communication of uncertainty is needed, so users understand that confidence bands do not represent exact predictions. Extreme rainfall on unstable snowpacks above glacial lakes creates compound hazards. This situation challenges the use of fixed thresholds and requires a shift towards more probabilistic, scenario-based communication strategies. Policy adoption gains momentum when partners can incorporate regular updates, co-signed advisories and operational dashboards into their planning process, rather than relying on isolated briefs.

Two areas require immediate attention. AI-assisted monitoring can improve coverage by filling gaps, identifying snow anomalies, and assessing the speed of glacier movement, with the findings then validated against field observations. Transregional collaboration with WGMS, WMO/GCW, and other programmes should progress beyond data exchanges to coordinated calendars, unified baselines, and joint statements at COPs and relevant fora. Ultimately, the durability of this strategy will stem not from new instruments but from institutionalised routines: predictable service delivery, transparent communication of uncertainties, and inclusive governance that sustains impact beyond project cycles. The overall RCS strategy framework is illustrated in Fig. 4.

3 Implementation Pathways

The RCS implementation pathway links strengthened observations, harmonised methods, and regional data systems to decision-relevant services. It sets out a phased implementation of standardised glacier, snow, and permafrost monitoring across RMCs, anchored in the operational guidelines, with country-level monitoring that is comparable and relevant to understanding the HKH at the regional scale. Field and remote-sensing observations will be routed through the HKH CryoHub as the regional entry point for FAIR, quality-assured and quality-controlled cryosphere data and derived products, enabling consistent assessments from local to regional scales. The pathway seeks to position the HKH more prominently in global scientific and policy arenas such as the IPCC, WMO, and COP negotiations by coordinating regional assessment inputs, contributing HKH datasets and case studies to global reports and monitoring systems, and convening joint science–policy dialogues so that the region's specific vulnerabilities and adaptation needs are systematically reflected in global agendas.

4 Conclusions

The HKH cryosphere is among the fastest-changing mountain regions globally. Without a coherent, long-term, and inclusive approach, uncertainties and inconsistencies will persist, adaptation windows will narrow, and social and economic losses will mount. The RCS offers a pragmatic response: basin-representative, standardised monitoring; a regional database system and CryoHub that supports findable, accessible, interoperable, and reusable (FAIR) data; capacity-building and shared instrumentation that strengthen all RMCs; and timely decision services with quantified uncertainty. This institutional and technical architecture is designed to convert heterogeneous observations into policy-ready knowledge. HKH Snow Watch seasonal updates support irrigation and hydropower decisions (Muhammad 2025, 2026; Muhammad and Thapa 2020, 2021); hazard intelligence couples PDGL watchlists with community-scale early-warning systems; and cryosphere syntheses reset baselines and update regional, national, and sectoral planning. Cross-cutting commitments to GESI, ethics, and safety in fieldwork, data management, and service delivery are treated not as add-ons but as operational capabilities that expand observability, strengthen legitimacy, and improve risk communication. Beyond the HKH, several design principles emerging from this strategy may be relevant for other mountain regions. These include: a co-governed regional node that complements rather than replaces national systems; standardised monitoring requirements across glacier, snow, and permafrost components; interoperable data and FAIR principles embedded from the outset; explicit links between observations, services, and policy processes; and built-in attention to GESI and ILK. With strong RMC leadership and ICIMOD's facilitative role, this architecture provides a transferable template for transitioning from fragmented, project-oriented cryosphere initiatives towards sustained, interoperable observation and service systems. The RCS will give policymakers and other decision-makers clear, timely, and regional-scale evidence on cryosphere

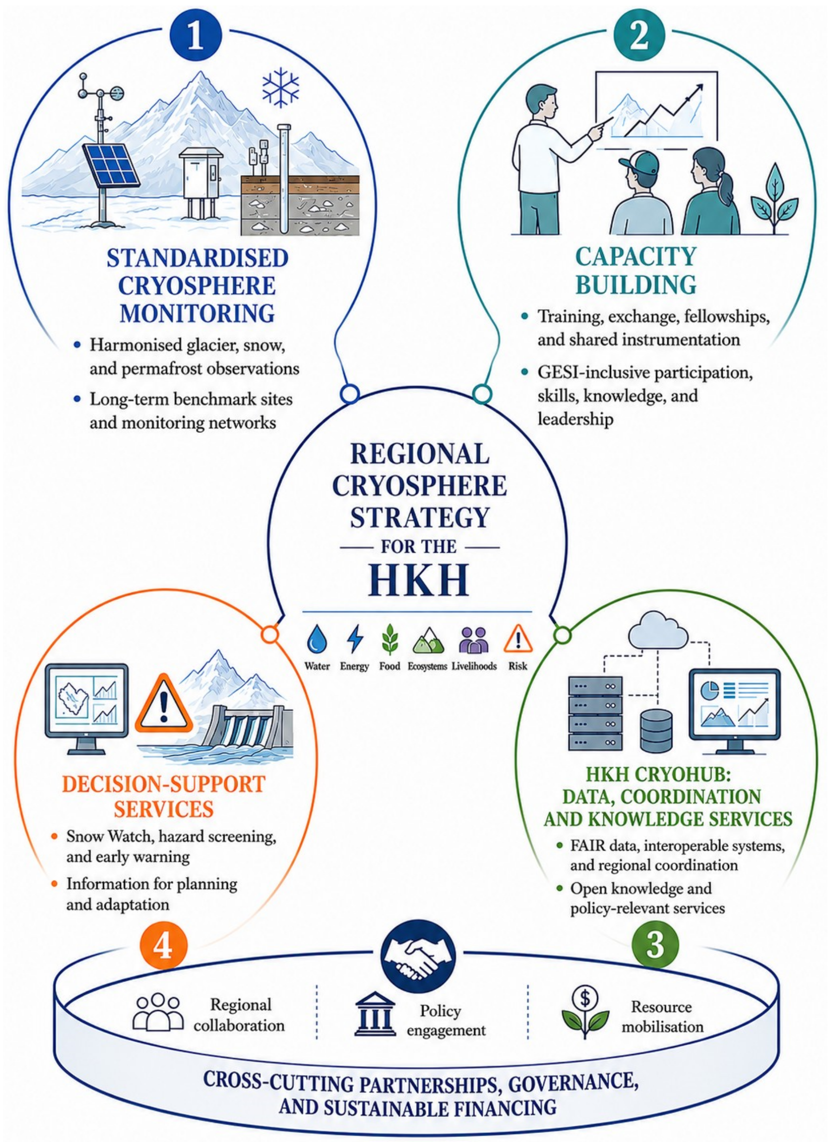

Fig. 4 Conceptual framework of the HKH Regional Cryosphere Strategy (RCS), illustrating its core components, functions, and cross-cutting commitments.

trends and risks. This will support climate-change decision-making through recommendations for global climate negotiations, targeted policy briefs, and decision-support products.

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Author Contributions

Sher MUHAMMAD: Conceptualization; Writing – original draft; Writing – review & editing. Mohd Farooq AZAM: Writing – original draft; Writing – review & editing. Miriam JACKSON: Writing – original draft; Writing – review & editing. ZHANG Qianggong: Writing – review & editing.

Ethics Declaration

Availability of Data and Materials: No primary data were used in this Perspective.

Conflicts of Interest: The author, ZHANG Qianggong, is the scientific editor of Journal of Mountain Science. He was not involved in the journal's review of, or decisions related to, this manuscript. The authors declare no conflicts interest.

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