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Climate Change Impact on Fresh Water Flow and Hydropower in the Himalayan Region

Ajay Pradhan
CEO, Cetus Consulting Solution Services Pvt Ltd, New Delhi

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***Corresponding author:** Ajay Pradhan
Email: ajay.pradhan@c2s2.in

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Abstract

This paper examines how climate change is reshaping the hydrological dynamics and hydropower infrastructure development in the Upper Ganges Basin of Uttarakhand, India. Drawing on field observations, consulting project experience, and multi-methodology hydrological analysis, the study identifies critical vulnerabilities affecting hydropower projects: sediment accumulation from landslides, Glacial Lake Outburst Floods (GLOFs), avalanche events, and seismic-induced erosion. Two major disaster events, the 2013 Kedarnath floods and the 2021 Chamoli rockslide-triggered flash flood, serve as case studies demonstrating compounding climate and structural hazards. The analysis emphasizes the urgent need for integrated risk assessment, real-time monitoring systems, and adaptive design standards for sustainable hydropower development in high-mountain regions vulnerable to rapid climate change.

Keywords: Climate change: Hydropower resilience: Himalayan hydrology: Disaster risk: Glacial lake hazards: Sediment management.

Introduction

The Himalayan mountain chain sustains ten of Asia's largest river systems, providing water, energy, and livelihoods to approximately 1.3 billion people across multiple nations (Eriksson et al., 2009). This region faces an unprecedented convergence of challenges: accelerating glacier retreat, intensifying monsoon variability, increased frequency of extreme precipitation events, and heightened seismic activity. These phenomena directly threaten the sustainability and safety of hydropower infrastructure, which has become a cornerstone of energy policy in mountain-bordering countries. Given the scale of hydropower investment and population vulnerability in downstream areas, understanding climate-hydropower interactions at the basin level rather than at individual project sites is essential for effective adaptation planning (Viviroli et al., 2011). This paper contributes to that understanding by synthesizing field data, consulting experience, and disaster documentation from the Upper Ganges Basin, one of India's most hydropower-intensive and climatically vulnerable regions.

Regional Climate Patterns

The Himalayan climate exhibits pronounced east-west differentiation driven by competing monsoon systems and orographic effects. The eastern slopes receive moisture from the Indian summer monsoon for approximately eight months (March-October), yielding annual precipitation exceeding 12,000 mm in some locales. The central ranges experience four months of significant monsoon influence (June-September), while the western reaches receive precipitation for only two months (July-August) (Chalise et al., 2001). This gradient directly impacts snow and ice accumulation patterns critical for dry-season river discharge. Winter precipitation arrives via westerly disturbance systems, particularly affecting the higher elevations (>3,000 masl). At these altitudes, precipitation falls predominantly as snow, feeding an interconnected network of glaciers that blanket over 112,000 km² of the greater Himalayan region—the world's third-largest ice reserve outside polar regions (Dyurgerov et al., 2005).

Glacial Water Systems and Seasonality

The timing and contribution of glacial melt to river systems varies significantly across sub-basins. In some drainage areas, glacial and snowmelt constitute only 2% of annual flow; in others, particularly the upper Indus and Ganges systems, melt contribution reaches 30-50% of annual discharge (Immerzeel et al., 2010). This seasonal pattern creates a dual-flow regime: high discharge during snow/ice melt seasons (April-June and post-monsoon months) and reduced flow during winter months when melt is minimal and the monsoon has retreated. Critically, many river basins exhibit a seasonal paradox: maximum precipitation occurs during monsoon months (June-September), yet the contribution from direct rainfall and melt often exceeds the storage capacity of river channels, leading to widespread inundation. Conversely, during dry winter months, glacial melt becomes the primary water source for irrigation, hydropower, and drinking water supplies across large population centers downstream.

Observational records and satellite data reveal consistent warming trends across the Himalayan region Shrestha et al., 1999). In the Chamoli area specifically, maximum temperatures have increased at 0.032°C annually (1980-2018), statistically significant at the 99.9% confidence level. January 2021 recorded the warmest temperatures in Uttarakhand in more than six decades (IMD,2021). These warming trends directly correspond to accelerated glacier retreat and altered melt-season timing. A recent comprehensive analysis concluded that Himalayan glaciers are retreating at roughly twice the rate observed during the 1975-2000 period (Brun et al., 2017). If current warming trajectories persist, more than one-third of the world's remaining glaciers including significant portions of the Himalayan ice cover, could disappear by 2100 (Marzeion et al., 2014). This prospect poses severe implications for seasonal water availability, particularly for hydropower projects designed on historical hydrological records.

Hydrological Analysis Methods for Mountainous Regions

Multi-method approaches that capture both current conditions and long-term trends are necessary for the assessment of water availability and climate impacts in mountainous locations (Huss et al., 2015). Seasonal and annual mass change can be directly measured using in-situ networks of stakes and pits positioned on glacier surfaces. Although logistically difficult in remote high-altitude terrain, this approach is regarded as the gold standard for accuracy and produces extensive spatial information on mass balance fluctuation (Cogley et al., 2011). Surface elevation changes over vast glacier areas and long time periods can be measured thanks to Digital Elevation Models (DEMs), which are created from airborne/satellite images and laser scanning. Although it takes careful calibration and interpretation, this approach gets over accessibility limitations (Hugonnet et al., 2021). By deducting estimated precipitation from measured runoff, a water-balance framework calculates basin-level mass balance. The residual is interpreted as net change in water storage (including glacier mass change). Sparse precipitation and discharge gauge networks in the Hindu Kush Himalaya region make this approach difficult (Racoviteanu et al., 2007). Over decades, repeated, spatially continuous data of glacier characteristics (area, length, surface elevation, ablation rates, albedo, equilibrium line altitude) are provided by satellite and aerial platforms. Although spatial resolution is still a constraint in small valleys, remote sensing has become essential for large-scale glacier monitoring (Kaab et al., 2015).

Water Availability in the Upper Ganges Basin: Chamoli District

The Upper Ganges Basin in Uttarakhand encompasses numerous glacial-fed rivers originating from peaks exceeding 7,000 meters. The Alaknanda River—originating at 3,641 masl near Badrinath from glaciers fed by Chaukhamba peak (7,140 m)—constitutes the primary drainage system in Chamoli District, traversing 229 km before confluence with the Bhagirathi at Devprayag to form the Ganges proper (CGWB,2014). The basin is characterized by four distinct seasons: severe winters (December-February), warm pre-monsoon months (March-May), intense monsoon precipitation (June-September), and post-monsoon transition (October-November). The study region's positioning in India's highest seismic zone (Zone V per BIS 2000), combined with intense weathering processes, creates a landscape of frequent landslides, avalanches, and episodic erosion events (BIS.2002). Rainfall distribution across Uttarakhand shows strong altitudinal and spatial gradients. In the Lesser Himalayan Zone (1,000-3,000 m), 70-80% of annual precipitation occurs during the monsoon season, with August typically the wettest month (India WRIS,2021). Average annual precipitation in Chamoli ranges from approximately 900-1,250 mm, though year-to-year variability is substantial—2003 recorded only 986 mm against the long-term normal of 1,230.8 mm. This variability amplifies drought and flood risk alike.

Winter precipitation, accounting for 17% of annual totals, arrives via westerly disturbance systems and typically falls as snow above 3,000 m. Pre-monsoon and post-monsoon months contribute approximately 7% each, often in the form of thunderstorm activity. Himalayan glaciers serve as critical freshwater reserves, slowly releasing stored ice and snow through melt processes. Current data indicates that glacier melt contributes 12-30% of annual streamflow in major basins like the Ganges, with peak melt occurring in late spring and early summer (April-June) prior to monsoon onset (Hasson et al., 2017). However, this relationship is non-linear and climate-sensitive: as glaciers shrink, the absolute volume of annual melt declines, while the geographic timing becomes compressed into shorter periods.

The implication for hydropower operations is significant: projects designed to capture peak melt-season flows may encounter reduced, more variable flows in coming decades, while simultaneously facing increased risk from extreme precipitation and GLOF events.

Hydropower Development in the Himalayan Region: Challenges and Systemic Issues

Environmental and Social Assessment Deficiencies

Hydropower is widely promoted as a climate-mitigation technology due to its low greenhouse gas emissions relative to fossil fuel alternatives. However, dam and run-of-river projects impose substantial environmental, social, and geological impacts, particularly in biodiverse and seismically-active mountain regions (Mongillo et al., 2011). The Hindu Kush Himalaya region contains globally significant biodiversity hotspots. Large-scale hydropower development disrupts critical habitats for terrestrial and aquatic species, fragmenting migration corridors and altering riparian ecosystems (Aggarwal et al., 1999). Deforestation associated with project construction accelerates erosion and downstream sedimentation while compromising livelihoods of forest-dependent communities (Sharma et al., 2021). A critical assessment gap exists in India's environmental clearance framework: projects <25 MW capacity is exempt from Environmental Impact Assessment (EIA), Social Impact Assessment (SIA), public consultation requirements, or mandatory monitoring plans (MoEFCC, 2006). Even for larger projects (>25 MW), the quality and comprehensiveness of environmental and social impact documentation often fall below international standards (Sandrp,2015). Furthermore, no cumulative impact assessment—evaluating the collective effects of multiple projects on river basins and their carrying capacities—has been systematically conducted for Uttarakhand's hydropower portfolio. The Expert Appraisal Committee (EAC) responsible for reviewing environmental clearances of river valley projects rarely objects to proposed developments. Environmental compliance monitoring, even where mandated, remains inadequate (Mukerji and Choo, 2020).

A fundamental structural deficiency in project approvals is the absence of systematic disaster risk assessment. Environmental and technical assessments do not incorporate analysis of project exposure to climate-induced hazards (GLOFs, avalanches, landslides, seismic ground motion). Yet, every hydropower facility in the study region faces significant exposure to one or more of these threats (NCS, 2021). Until disaster risk assessment becomes mandatory at project conception and design stages, hydropower infrastructure will remain chronically vulnerable.

Technical Risks Affecting Hydropower Operations

Himalayan rivers transport exceptionally high sediment loads, derived from glacier erosion, bedrock weathering, active landslide zones, and seismic disturbances, into reservoirs. Sedimentation processes unfold in predictable stages. Upon reservoir impoundment, reduced flow velocities trigger immediate sediment deposition (Morris et al., 2008). Coarse materials settle in upstream reaches while fine sediments progress downstream, progressively infilling the reservoir (Kondolf et al., 2014). Over years to decades, coarse sediments continue accumulating while fine materials approach equilibrium between inflow and outflow (Williams et al., 1984). In mature, stable systems, sediment inflow and outflow equalize across all grain sizes. However, this equilibrium state is rarely achieved in Himalayan systems due to continued high sediment inputs and climate variability (Vorosmarty et al., 2003). Most of the world's existing reservoirs currently operate in Stage 1, losing 0.5-1% of total storage volume annually to sedimentation (Syvitski et al., 2005). This depletion reduces global per capita reservoir storage to levels that existed 60 years ago—representing a cumulative infrastructure depreciation crisis (Vogt et al., 2007).

Fine-grained sediments exhibit lower shear resistance and higher at-rest pressure coefficients compared to consolidated rock or coarser materials. Conventional dam design typically accounts for at-rest soil pressure coefficients around 0.39 and internal friction angles of 37°, but actual sediment properties in Himalayan reservoirs often deviate substantially from these assumptions, increasing structural stress (Seed and Clements, 1977). Progressive sedimentation reduces spillway approach depth and can clog low-level outlets, compromising flood attenuation capacity and reservoir drawdown capabilities. During large floods, reduced spillway capacity may necessitate emergency spillway activation, with potential for uncontrolled overflow and downstream hazards (Brandes, 1997). Sediment-laden water abrading turbine blades causes surface degradation, material loss, and efficiency decline. Extended shutdown periods for maintenance or component replacement impose significant economic costs and energy supply disruptions (Thakur and Kumar, 2015). Advanced materials (stainless steel, tungsten carbide coatings) provide some protection but add substantial capital costs (Grunewald and Pichel, 2005).

Glacial Lake Outburst Floods: A Multi-Decadal Hazard

Glacial Lake Outburst Floods (GLOFs) represent a class of catastrophic hazard in mountain regions, particularly where hydropower infrastructure is concentrated in river valleys downstream of moraine-dammed lakes (Hugge lei al., 2002). As glaciers retreat and melt, meltwater accumulates behind natural dams composed of glacial moraine, avalanche debris, or tributary-dammed configurations. These natural barriers, lacking engineering design or maintenance, are inherently unstable (Mergili and Schneider, 2011). Lake water levels rise seasonally with melt input and can exceed dam crest heights during unusually large melt events or heavy rainfall (Worni et al., 2010). Breaching occurs through overtopping erosion, seepage-induced failure, or sudden rupture, releasing massive water volumes and entrained sediment downstream in minutes to hours (Walder and O'Connor, 1997). Documentation of GLOF events in the 20th century Himalayan region identified dozens of lake breaches, with outburst peak discharges reaching 1,500-2,500 m^3/s in some cases (Ives, 1989). The 1985 Langmoche Glacier lake breach in Nepal generated a flood with peak discharge (~2,000 m^3/s) that devastated a nearly-completed hydropower project, destroying nine years of planning and construction effort.

Hydropower projects are designed based on historical flood frequency data—typically the 100-year or 500-year flood magnitude derived from streamflow records. However, GLOF peak discharges often exceed these design thresholds dramatically and unpredictably (Richardson and Reynolds, 2000). A comprehensive modeling study combining glacial lake inventories with breach dynamics and flood-routing models estimated that approximately 50% of modeled GLOFs exceed the estimated 100-year meteorological flood within 20 km downstream of source lakes (Schwanghard et al., 2016). Only the largest events reach 85 km+ downstream (Ponce et al., 2003). This spatial distribution of GLOF hazard directly overlaps with planned and operational hydropower project locations in Sikkim, eastern Nepal, and Bhutan.

Peak discharge estimates at breach sites vary by two orders of magnitude for a given lake surface area, primarily reflecting uncertainties in lake bathymetry, breach geometry, and breach erosion rate (Fujita et al., 2013). Smaller lakes exhibit greatest uncertainty in depth and volume estimates; larger lakes introduce uncertainty from breach depth and erosion rate assumptions (O'Connor and Beebee, 2009). Downstream, flood attenuation processes reduce peak discharge more rapidly for GLOFs than for meteorological floods due to the concentrated, short-duration hydrograph of outbursts. Consequently, impact reaches (zones where GLOF discharge exceeds 100-year flood) narrow downstream, but uncertainties persist for several tens of kilometers (Virkkunen and Makinen et al., 2004). For hydropower projects planned or under construction in headwater reaches, uncertainties in peak discharge may be twice as large as for existing operational projects positioned further downstream. This asymmetry suggests heightened risk exposure for newer developments.

Secondary Hazards: Avalanches and Seismic Destabilization

Rapid mass movements from glacier detachment and avalanche phenomena can trigger flash floods independent of, or superimposed upon, GLOFs. These events block access roads to power facilities, damage intake structures and penstocks, and deposit sediment in reservoirs. Secondary operational impacts include:

- Turbine efficiency losses from increased suspended solids in water
- Desander and settling basin overload requiring intensified cleaning operations
- Filter and settling tank failure from elevation in dissolved and suspended solids within weeks of avalanche events
- Extended downtime for component repairs, compounded by difficult terrain access (Thakur and Kalura, 2015).

The Himalayan region experiences active crustal deformation along the Indo-Australian plate boundary, generating frequent earthquakes. Uttarakhand lies within Seismic Zone V (MSK intensities exceeding IX possible), with major thrust faults—including the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT)—hosting repeated seismic ruptures (NCS, 2020). Large earthquakes trigger widespread rock falls, landslides, and slope failures, destabilizing soil and deposits along river corridors. Post-earthquake, soils become looser and more prone to remobiliza (IMD, 2013). In seismic zones, a GLOF occurring weeks or months after a major earthquake could mobilize earthquake-destabilized sediment, amplifying outburst magnitude and impact (Lin et al., 2006).

Case Study 1: The 2013 Kedarnath Disaster

In June 2013, a convergence of climate and hydrological factors triggered catastrophic flooding in the Kedarnath valley of Uttarakhand (Wadia Institute of Himalayan Geology, 2013). The southwest monsoon arrived approximately two weeks ahead of its climatological normal timing, accelerating snowmelt in high-altitude basins (IMD, 2013). The monsoon system stalled over the region, depositing rainfall well in excess of historical seasonal norms (Allen et al., 2015). On June 16, 2013, a concentrated convective system deposited at least 300 mm of rain within hours over the Alaknanda and Bhagirathi headwaters (Petley, 2013).

The June 2013 cloudburst, combined with accelerated snowmelt, overwhelmed the small natural dam retaining Chorabari Lake, a glacial lake located at 3,960 m elevation approximately 2 km upstream of Kedarnath temple. Satellite and field evidence indicates the lake—measuring 400 m × 200 m × up to 20 m depth—released its entire 400,000 m^3 water volume in approximately 10 minutes (Petley et al., 2005). This outburst, superimposed upon already-elevated monsoon flows, created a catastrophic flood wave that swept down the Mandakini River valley. The combined flood waters descended steep terrain, overtopped riverbanks and impacted communities and infrastructure across Kedarnath, Rambara, Gaurikund, Sonprayag, and surrounding areas (Kumar et al., 2006). More than 100 secondary landslides were triggered by flood momentum and bank erosion, affecting over 1,000 km of transport infrastructure (Srivastava, 2013).

Hydropower projects in the impact zone suffered extensive damage (UJVNL, 2013). A penstock tunnel, completed in April 2013, was completely washed away in the June flood. Project delayed indefinite due to access and safety constraints (CEA, 2014). Flood waters destroyed concrete structural work, delaying commissioning from 2017 to 2018, with further delays likely due to transport infrastructure instability (IEA, 2014). Both dams sustained significant damage to structural elements. A joint assessment by the World Bank and Asian Development Bank estimated direct damage to public infrastructure (roads, water supplies, buildings) at approximately USD $700 million (World Bank and Asian Development Bank, 2013). Indirect economic losses, including tourism disruption and agricultural damage, remained uncalculated. The Kedarnath disaster exposed critical vulnerabilities:

- Insufficient GLOF risk assessment during project design
- Lack of real-time flood monitoring and early warning systems
- Inadequate emergency spillway capacity and sediment management
- Poor coordination between hydropower operations and disaster management authorities
- Absence of cumulative risk assessment across multiple projects in the basin

Case Study 2: The 2021 Chamoli Rockslide-Induced Flash Flood

On February 7, 2021, the Chamoli District of Uttarakhand experienced a catastrophic flash flood originating from a massive rockslide on the north slope of Ronti Peak (5,500+ masl) (Kaab et al., 2021). Satellite imagery and DEM analysis revealed that the failure had originated in precursor movements dating to late 2016, when an ice avalanche had released approximately 1.5 × 10^7 m^3 of ice and rock debris (Jacquemart and Loso, 2019). The 2016 avalanche event had fractured and destabilized the headwall, removing lateral ice support and exposing fractured rock to intensified solar radiation and freeze-thaw cycling (Gruber and Haeberli, 2007). Over the intervening four years (2016-2021), these weakening processes accelerated due to increased maximum temperatures by 0.032°C annually from 1980-2018 at Chamoli (Kumar et al, 2020), progressive stress redistribution following the 2016 ice avalanche, greater diurnal temperature fluctuations at the fracture zone as ice cover diminished and preceding February 7, 2021 (Gobiet et al., 2014). DEM differencing analysis of pre-event (2016) and post-event (February 7, 2021) imagery revealed the following failure geometry:

- Failure zone dimensions: 550 m wide crest, extending from 5,500 masl to approximately 4,500 masl (1,000 m vertical drop)
- Scarp depth: 150 m average, up to 200 m maximum
- Scarp length: 1,060 m
- Affected area: ~350,000 m²
- Volume estimate: 22 million m³ (from vertical differencing); cross-validation via field inspection and modeling yielded 25 million m³ (Rankl et el., 2014).
- Composition: Approximately 85% bedrock, 15% ice (based on modeled glacier thickness for small hanging glacierettes) (Farinotti et al., 2017)
- Total mass: ~52 × 10⁹ kg (Kaab et al., 2015)

The rockslide mass, traveling at high velocity down the steep terrain, impacted the glacierette at the base of the scarp and mobilized in a debris flow configuration. This mass, combined with rapid snowmelt and rainfall-generated streamflow, generated a debris-laden flood wave that traversed the Rishi Ganga and Dhauliganga valleys downstream (Vinnell and Ashmore, 2020). Analysis of temperature records for Chamoli indicates that January 2021 recorded the warmest temperatures in six decades for Uttarakhand (Pai et al., 2013). The maximum temperature trend (0.032°C/year increase) is statistically significant at the 99.9% confidence level. These warming trends directly reduce glacier and permafrost stability, accelerate melt-driven stress changes in ice-rock interfaces, and enhance freeze-thaw weathering—processes that collectively explain the 2016-2021 destabilization sequence (IPCC, 2021). The 2021 event was not an anomaly but rather a manifestation of systemic climate-driven changes in mountain stability across the Hindu Kush Himalaya region.

Policy and Management Recommendations

Every hydropower project in the Himalayan region, whether under design, construction, or operation, should undergo a comprehensive disaster risk assessment that evaluates exposure to:

- Glacial lake outburst floods (with documented lake inventories and breach-scenario modeling)
- Avalanche and rockslide hazards (incorporating climate-driven stability changes)
- Seismic triggers and earthquake-induced erosion
- Landslide-derived sediment yields
- Cumulative hazard scenarios (e.g., GLOF during high base flow from monsoon, or earthquake triggering GLOF)

This assessment must be conducted by multidisciplinary teams including geomorphologists, hydrologists, climatologists, and engineers, with results transparently shared with communities and regulatory agencies (UNISDR, 2015). Hydropower facilities should invest in Internet-of-Things (IoT) based monitoring networks providing 24/7 assessment of (Teale et al., 2016):

- Upstream hazard signals: Glacial lake water levels, moraine dam integrity, acoustic signatures of incipient failure
- Streamflow and sediment dynamics: Real-time discharge measurement, suspended sediment concentration, turbidity
- Operational parameters: Intake structure blockage, sediment trap efficiency, spillway flow rates
- Climate variables: Precipitation, temperature, snow cover extent, incoming solar radiation

Early warning protocols, coordinated with disaster management authorities, should enable automated reservoir drawdown or spillway activation if hazard thresholds are exceeded. Future hydropower projects should be designed with adaptive capacity to accommodate:

- Increased sediment yields: Oversized sediment traps, periodic flushing protocols, sediment bypass tunnels
- Larger probable maximum floods: Spillway capacity re-evaluated using climate-informed precipitation extremes, not historical records alone
- Altered flow seasonality: Storage capacity adjusted to capture extended dry seasons expected in 2050-2100 climate scenarios
- Enhanced erosion-resistant materials: Turbine blades and penstock linings should employ advanced composites or coatings resistant to high-velocity sediment abrasion (Annandale, 2013)

No single hydropower project operates in isolation. Cumulative impacts of multiple projects, including fragmented river flows, altered sediment transport, thermal changes, and compound hazard exposure, must be assessed at the basin level. Uttarakhand's 50+

existing, under-construction, and proposed hydropower projects require integrated basin-level environmental and social impact analysis, with results informing portfolio-level development decisions (Hirji and Davis, 2009). Local communities in headwater regions possess generational knowledge of water availability, precipitation patterns, and hazard occurrence. Participatory monitoring networks integrating scientific instrumentation with community observation can enhance early warning effectiveness and build local capacity for adaptation (Bernett and Waters, 2016).

Conclusions

The Himalayan region stands at an inflection point. Climate change is fundamentally altering the hydrological cycle upon which both natural ecosystems and human infrastructure depend. Hydropower development, while offering climate-mitigation potential through displaced fossil fuel generation, introduces new vulnerabilities when designed and operated without rigorous climate risk integration. The 2013 Kedarnath and 2021 Chamoli disasters are not aberrations but canaries in the coal mine, signals of the magnitude of hazard exposure facing hydropower infrastructure in mountain regions. Both events demonstrated the cascading consequences of inadequate risk assessment, insufficient monitoring, and design standards disconnected from climatic reality. Transitioning to sustainable, resilient hydropower development in the Himalayas requires (ICIMOD, 2021):

1. Mandatory disaster risk assessment as a precondition for project approval
2. Real-time IoT monitoring systems providing early warning of hazard onset
3. Adaptive design standards reflecting mid-21st century climate projections, not historical averages
4. Basin-level cumulative impact analysis informing portfolio development decisions
5. Community-centered adaptive management integrating local knowledge with scientific monitoring

These measures demand increased capital investment and operational complexity. However, the cost of infrastructure failure in terms of economic losses, loss of life, and undermined public confidence in hydropower, far exceeds the investment required for climate-adapted, resilient systems. The window for redesigning hydropower infrastructure remains open but is rapidly closing. Decisions made in the coming 3-5 years will determine whether the hydropower sector in the Himalayan region becomes a model of climate adaptation or a cautionary tale of infrastructure maladaptation.

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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