FOREST COVER CHANGE AND HYDROPOWER SUSTAINABILITY IN NEPAL: A CLIMATE VULNERABILITY ASSESSMENT

Abstract

Nepal's ambitious hydropower expansion and recent forest cover recovery are both threatened by accelerating climate change, yet the linkages between forest dynamics and hydropower sustainability remain poorly integrated. This study assesses how forest cover changeincluding deforestation, afforestation, and species composition shiftsinteracts with climate-induced hydrological alterations to affect hydropower viability across three Nepalese catchments: Kulekhani, Bhote Koshi, and Ratuwa. Using Landsat/Sentinel time-series (1990–2020), SWAT hydrological modeling under CMIP6 scenarios (SSP2-4.5, SSP5-8.5, 2030–2050), and an integrated Climate Vulnerability Index (CVI), we quantified forest change impacts on dry-season baseflow and sediment yield. Results show that while total forest cover increased in Kulekhani (+3.9%) and remained stable in Bhote Koshi, pine monoculture expansion (from 18% to 32% of forest area) exacerbated dry-season flow reduction (from 22% to 31%) and sediment increase (from 52% to 78% under high emissions). Broadleaf regeneration partially mitigated these impacts. Ratuwa's ongoing deforestation (dense forest declined from 42% to 27%) could reduce dry-season baseflow by nearly 50% by 2050. The CVI ranked Bhote Koshi (0.73) and Kulekhani (0.68) as high vulnerability, with Ratuwa reaching high vulnerability (0.66) if deforestation continues. Weak policy coordination between forestry and energy sectors was evident across all catchments. We recommend prioritizing native broadleaf forest restoration in hydropower catchments, supported by payment for ecosystem services, to sustain dry-season flows, reduce sedimentation, and enhance climate resilience.

Keywords: Forest cover change; hydropower sustainability; climate vulnerability; Nepal; eco-hydrology; SWAT modeling

Introduction

Nepal, a Himalayan nation characterized by extreme topographical and climatic heterogeneity, is confronting the compounded pressures of rapid climate change, ambitious infrastructure development, and evolving land use dynamics. Despite contributing only 0.027% of global greenhouse gas emissions, Nepal ranks as the fourth most climate-vulnerable country in the world, facing accelerated glacier melt, erratic monsoon patterns, and increased frequency of extreme weather events (Adhikary & Aryal, 2025; UNDP, 2025). This vulnerability directly threatens two of the nation's most strategic natural assets: its expansive forest cover and its vast hydropower potential. Forests, which have rebounded from approximately 25% of land area in the 1990s to nearly 45% by 2016, serve as the backbone of Nepal's carbon neutrality strategy and community livelihoods (Oldekop et al., 2024; Kandel, 2025). Meanwhile, hydropowerwith a theoretical capacity of 83,290 MW and an economically feasible potential of around 42,000 MWhas been positioned as the cornerstone of Nepal's clean energy transition and a major export commodity (Bhandari et al., 2025; Sharma et al., 2025). However, the sustainability of both forests and hydropower is increasingly compromised by climate-induced hydrological shifts and land-use changes that have been studied largely in isolation, creating a critical knowledge gap that this paper addresses.

The cryosphere of the Himalayaoften called the "Third Pole"is warming at a rate significantly higher than the global average, with profound consequences for Nepal's water systems. Glaciers across the Nepalese Himalaya are retreating at an accelerated pace, and glacial lake volumes have expanded by nearly 45% between 2000 and 2020 (Adhikary & Aryal, 2025; Climate Reality Project India, 2025). This rapid melt initially increases river discharge but leads to long-term reductions in dry-season flows, directly affecting run-of-river hydropower plants, which constitute the vast majority of Nepal's hydropower fleet. Moreover, the number of dangerously large glacial lakes has increased, with 21 lakes currently classified as potentially hazardous, and six as high-risk (UNDP, 2025; Bhandari et al., 2025). Glacial Lake Outburst Floods (GLOFs) have already caused catastrophic damage: in July 2025, a GLOF in Rasuwa district killed nine people, destroyed a major suspension bridge, and severely damaged a 25 MW hydropower facility. Such events are becoming more frequent, and climate models project a further intensification of extreme precipitation and landslide activity, which together increase sediment loads and reduce the operational lifetime of reservoirs and turbines (Lohani Sitoula, 2024; Source 2, 2024). Consequently, the hydropower sectorplanned to reach 28,500 MW by 2035 under Nepal's Nationally Determined Contributions (NDCs)faces a fundamental question: can it remain sustainable when the very hydrological regimes it depends on are being fundamentally altered by climate change?

Parallel to these cryospheric and hydrological changes, Nepal has witnessed a remarkable but ecologically complex transformation of its forest cover. Between 1992 and 2016, forest area expanded from 25.4% to 44.7% of total land, driven by successful Community Forest User Group (CFUG) programs, out-migration of rural labor leading to agricultural abandonment, and natural regeneration on degraded hillsides (Oldekop et al., 2024; Sharma et al., 2025). However, not all forest regrowth is ecologically equal. Extensive areas have been colonized by non-native or monospecific pine plantations, which often reduce groundwater recharge, lower dry-season baseflows, and increase surface runoff and erosion compared to native broadleaf forests (Kandel, 2025; Chaudhary & others, n.d.). In addition, while community forestry has improved canopy cover, it has also led to the extraction of leaf litter and understory biomass, which can degrade soil infiltration capacity and alter the water-holding function of the forest floor (Bhandari et al., 2025; Source 4, n.d.). These eco-hydrological changes have direct, measurable impacts on river flow regimes. For example, in the Roshi and Melamchi watersheds, areas with higher broadleaf forest cover maintained more stable spring flows during the dry season, whereas pine-dominated catchments showed a 15–20% reduction in baseflow (Chaudhary & others, n.d.; Kandel, 2025). This evidence underscores that forest cover change is not merely a carbon storyit is a water story with direct implications for hydropower sustainability.

The interplay between forest cover dynamics and hydropower viability operates primarily through two mechanisms: regulation of streamflow and control of sediment yield. Healthy, mixed-species forests with intact understory and deep root systems act as natural sponges, slowing monsoon runoff, enhancing groundwater recharge, and releasing water gradually during the dry season (Lohani Sitoula, 2024; Oldekop et al., 2024). Conversely, deforestation, forest degradation, or poorly designed afforestation (e.g., monoculture plantations) can reduce infiltration by up to 30% and increase overland flow during storms, raising peak flood discharges while diminishing dry-season baseflow (Sharma et al., 2025; Adhikary & Aryal, 2025). For run-of-river hydropower projects, which lack storage reservoirs, this translates into power generation volatility: excess monsoon flows may exceed turbine capacity or cause damage, while dry-season deficits force plant shutdowns.

Sedimentation presents an equally severe challenge. Nepal’s young, fragile geology already yields some of the highest sediment loads per unit area in the world. Accelerated erosion from forest cover loss, road construction, and climate-intensified rainfall has caused reservoir sedimentation rates far exceeding design assumptions. The Kulekhani hydropower project, Nepal’s only storage-type plant, has lost an estimated 25% of its initial storage capacity due to sedimentation within three decades of operation (Bhandari et al., 2025; Source 2, 2024). For new projects planned in steep, forested catchments, failure to account for forest-mediated sediment dynamics could lead to premature decommissioning and stranded assets.

Despite these clear biophysical linkages, Nepal’s policy and planning frameworks treat forests and hydropower as separate sectors with weak institutional coordination. The current NDC targets (70% forest cover maintained and 28,500 MW renewable energy capacity by 2035) are commendable, but they lack an integrated strategy to manage the trade-offs and synergies between upstream forest management and downstream hydropower generation (Source 3, n.d.; Lohani Sitoula, 2024). Environmental Impact Assessments (EIAs) for hydropower projects routinely evaluate direct impacts on vegetation and wildlife but rarely assess how forest cover change in the wider catchmentdriven by agriculture, infrastructure, or community forestry practiceswill alter long-term hydrological services (Kandel, 2025; Bhandari et al., 2025). Similarly, community forestry operational plans seldom incorporate downstream water users (including hydropower plants) as stakeholders, despite clear evidence that upstream land use affects power reliability (Oldekop et al., 2024; Chaudhary & others, n.d.). This governance fragmentation is exacerbated by climate change, which introduces non-stationarity into hydrological systemsmeaning that historical flow data no longer reliably predict future conditions. Therefore, a new analytical framework is urgently needed, one that explicitly assesses the climate vulnerability of the forest-hydropower nexus.

Literature Review

Forest Cover Change and Its Hydrological Implications

Nepal has experienced a remarkable transformation in forest cover over the past three decades. Between 1992 and 2016, forest area increased from approximately 25.4% to 44.7% of the total land area. This recovery has been driven primarily by successful community forestry programs, out-migration of rural labor leading to agricultural abandonment, and natural regeneration on degraded hillsides (Oldekop et al., 2024; Sharma et al., 2025). However, this forest expansion is not hydrologically uniform. Research indicates that different forest types have vastly different effects on water regulation. In the Middle Hills of Nepal, large-scale afforestation has often favored Pinus roxburghii (chir pine), a fast-growing conifer with high evapotranspiration rates and low infiltration capacity, which significantly reduces groundwater recharge compared to native broadleaf forests (Kandel, 2025; Chaudhary & others, n.d.).

The eco-hydrological trade-off between pine plantations and mixed broadleaf forests has been documented in several watershed studies. In community forests of Gandaki Province, water yield under different tree species was measured, and results showed that natural regenerated broadleaf forests maintained higher dry-season baseflows, whereas pine-dominated catchments exhibited reduced streamflow and deeper groundwater tables (Water Yield Realization Study, 2022). This finding challenges the common assumption that any increase in forest cover automatically improves water availability. Instead, forest composition and management intensity matter critically for downstream water users, including hydropower plants (Lohani Sitoula, 2024).

Land cover change also includes agricultural expansion and infrastructure development. A comprehensive study of the Ratuwa River Basin in the Churia region quantified the effects of a 35% reduction in forest cover, a 20% loss of wetlands, and a 25% increase in agricultural land over three decades. These changes resulted in a 40%

increase in surface runoff, a 30% decrease in groundwater recharge, a 50% rise in flood frequency, and a 25% decline in the economic value of water regulation services (Kandel et al., 2025). Such watershed-scale degradation directly undermines the stability of river flows essential for hydropower generation.

Climate Change Impacts on Water Availability and Hydropower Infrastructure

Nepal is positioned at the frontline of climate-induced hydrological change. Despite contributing minimally to global greenhouse gas emissions, the country is the fourth most climate-vulnerable nation in the world, facing accelerated glacier melt, erratic monsoons, and increased extreme weather events (Adhikary & Aryal, 2025; UNDP, 2025). The Hindu Kush Himalaya, often called the "Third Pole," is warming at a rate significantly higher than the global average, with profound consequences for water systems. Glacial lakes have expanded by nearly 45% between 2000 and 2020, and 21 glacial lakes are currently classified as potentially dangerous, with six at high risk of Glacial Lake Outburst Floods (GLOFs) (Climate Reality Project India, 2025; Bhandari et al., 2025).

These hazards are not hypothetical. In July 2025, a GLOF in Rasuwa district killed nine people, destroyed a major bridge, and severely damaged a 25 MW hydropower facility. Earlier events include a 2016 GLOF that destroyed the Bhote Koshi hydropower plant at the Nepal-China border, a massive landslide in Jure (2014) that damaged multiple projects, and floods in eastern Nepal (June 2023) that damaged 30 hydropower plants with a combined capacity of 463 MW (ICIMOD, 2023; Adhikary & Aryal, 2025). These disasters illustrate that climate risks are already materializing and pose direct threats to energy infrastructure.

The mechanisms of climate impact on hydropower are threefold. First, seasonal shifts in runoff: glacier melt peaks earlier in the summer, reducing water availability later in the dry season when run-of-river plants need stable flows. Second, increased sediment loads: intense rainfall and landslides deliver excessive sediment to reservoirs and turbines, accelerating wear and reducing efficiency. Third, extreme events: floods can exceed design capacities, while droughts can force complete shutdowns (Bhandari et al., 2025; Lohani Sitoula, 2024). Given that more than 96% of Nepal's electricity comes from hydropower, predominantly run-of-river with minimal storage, the sector is exceptionally vulnerable to climate-induced hydrological variability.

Mechanisms Linking Forest Cover Change to Hydropower Sustainability

The relationship between upstream forests and downstream hydropower operates through two primary mechanisms: flow regulation services and sediment control functions. Healthy, diverse forests with intact understory and deep root systems act as natural sponges, absorbing monsoon rainfall, recharging groundwater, and releasing water gradually during dry periods (Oldekop et al., 2024; Sharma et al., 2025). Conversely, forest degradation, inappropriate afforestation (e.g., pine monocultures), or catchment disturbances increase surface runoff, reduce infiltration, and lower dry-season baseflows. For run-of-river hydropower plants, this translates directly into power generation volatility: excess monsoon flows may exceed turbine capacity or cause damage, while dry-season deficits force shutdowns (Devkota et al., 2023).

Sedimentation is an equally severe challenge. Nepal’s young, tectonically active geology naturally produces high sediment loads. However, human activitiesincluding deforestation, road construction, and improper land useexacerbate erosion. The Kulekhani-I hydropower project, Nepal’s only storage-type plant, provides a cautionary example. Designed for a 100-year operational life, the reservoir has lost an estimated 25% of its initial storage capacity within three decades due to sedimentation. Using remote sensing data (1988–2020), researchers found that reservoir area expansion was driven directly by sediment deposition originating from upstream soil erosion, landslides, and construction waste disposal (Rimal & Tiwary, 2024). This case clearly demonstrates that upstream forest condition and land management directly affect the economic lifespan of hydropower assets.

The species composition of forests further modulates hydrological services. In the Gandaki Province, community forests dominated by native broadleaf species maintained higher dry-season flows compared to pine plantations. Pine stands exhibit higher evapotranspiration and deeper groundwater tables, reducing the water available for streams during critical low-flow periods (Water Yield Realization Study, 2022; Kandel, 2025). This finding has profound implications for Nepal’s afforestation policies: planting pine for rapid carbon sequestration may inadvertently reduce dry-season river flows, harming both hydropower generation and downstream water users.

Policy Frameworks and Governance Fragmentation

Nepal’s policy landscape acknowledges the importance of forests and hydropower but fails to integrate them effectively. The Nationally Determined Contributions (NDCs) commit to maintaining at least 46% forest cover and expanding renewable energy capacity to 28,500 MW by 2035, yet the plans for achieving these targets operate in separate silos (Source 3, n.d.; Lohani Sitoula, 2024). The Hydropower Development Policy (2001) mandates a minimum environmental flow of 10% of the minimum monthly average flow but does not address upstream forest management as a tool to ensure that flow. Likewise, community forestry operational plans focus on forest products, carbon sequestration, and biodiversity, but rarely consider water regulation as an explicit objective or engage downstream hydropower operators as stakeholders (Chaudhary & others, n.d.; Oldekop et al., 2024).

A promising framework is the Water-Energy-Food-Ecosystem (WEFE) nexus. Researchers have developed a Climate, Land, Energy, and Water Systems (CLEWs) model for Nepal, which simulates interactions among climate policies, land use, energy production, and water resources. The model showed that Nepal's NDC scenario can reduce emissions while protecting water and land resources, but it also revealed trade-offs: aggressive hydropower expansion without catchment management leads to increased sedimentation and reduced reservoir life (Bhandari et al., 2023). This highlights the need for integrated planning that explicitly links forest condition to hydropower performance.

However, implementation remains weak due to data gaps and institutional fragmentation. Many critical watersheds lack long-term records of precipitation, temperature, and river flow, making it difficult to calibrate hydrological models or design adaptive management strategies (ICIMOD, 2023). Furthermore, community forestry practices have sometimes exacerbated water insecurity. In Nepal's Middle Hills, nearly 70% of springs are drying or have already dried up, and research suggests that while community forestry increased vegetation, it also reduced groundwater recharge because of high leaf litter extraction, soil compaction, and the spread of high-evapotranspiration species (Kandel, n.d.). This unintended outcome represents a classic eco-hydrological trade-off: more trees do not always mean more water.

Methodology

Study Area

Three catchments representing Nepal's major river systems and differing forest cover dynamics were selected: (1) **Kulekhani catchment** (Bagmati Province) – hosting the country's only storage-type hydropower plant, with known sedimentation issues; (2) **Bhote Koshi catchment** (Province No. 1) – a high-glacial influence catchment with run-of-river projects and recent GLOF events; and (3) **Ratuwa River catchment** (Churia region, Madhesh Province) – a lowland forest-agriculture mosaic with rapid land cover change. Table 1 summarizes the key characteristics of each study catchment.

Table 1: Characteristics of Selected Study Catchments in Nepal

Catchment	River System	Area (km²)	Elevation Range (m)	Dominant Forest Type	Hydropower Type	Climate Vulnerability Driver
Kulekhani	East Rapti	1,260	450–2,600	Mixed broadleaf, degraded pine	Storage (92 MW)	Sedimentation, land use change
Bhote Koshi	Koshi (Sunkoshi)	2,840	800–6,500	Alpine, sub-alpine, pine	Run-of-river (45 MW + 36 MW)	GLOFs, glacier melt, landslides
Ratuwa	Ratuwa (Koshi tributary)	1,870	80–1,200	Sal forest, agricultural mosaic	Small run-of-river (planned)	Deforestation, flood/drought variability

Data Source: Multiple data types were collected from national and global repositories, as detailed in Table 2.

Table 2: Data Sources and Descriptions

Data Category	**Data Type**	**Source**	**Resolution / Period**	**Purpose**
Land use/cover	Landsat 5, 7, 8; Sentinel-2	USGS/ESA	30 m, 1990–2020	Forest cover change detection
Topography	SRTM DEM	NASA	30 m	Watershed delineation, slope
Climate (historical)	Precipitation, temperature	DHM Nepal, CHIRPS	0.05°, 1990–2020	Hydrological model input
Climate (future)	CMIP6 GCMs (SSP2-4.5, SSP5-8.5)	IPCC, WorldClim	1 km, 2030–2050	Future scenario modeling
Hydrology	River discharge	DHM Nepal	Daily, 2000–2020	Model calibration/validation

Sediment	Suspended sediment load	Kulekhani HPP records, DHM	Monthly, 2010–2020	Sediment yield calibration
Hydropower	Plant capacity, design flow, sedimentation rate	NEA, IPPAN	Plant-specific	Vulnerability assessment
Forest management	Community forest operational plans, species maps	DoF, FECOFUN	GIS layers, reports	Forest type characterization

*Abbreviations: USGS = United States Geological Survey; ESA = European Space Agency; NASA = National Aeronautics and Space Administration; DHM = Department of Hydrology and Meteorology (Nepal); CHIRPS = Climate Hazards Group InfraRed Precipitation with Station data; CMIP6 = Coupled Model Intercomparison Project Phase 6; SSP = Shared Socioeconomic Pathway; NEA = Nepal Electricity Authority; IPPAN = Independent Power Producers' Association of Nepal; DoF = Department of Forests; FECOFUN = Federation of Community Forestry Users, Nepal.

Forest Cover Change Detection

Forest cover change was quantified using a time-series analysis of Landsat and Sentinel-2 imagery from 1990 to 2020, at five-year intervals. The Random Forest classifier was applied to classify land use into five categories: dense forest, open forest, shrub/grassland, agriculture, and barren/built-up. Accuracy was assessed using ground truth points from high-resolution Google Earth imagery and field visits (overall accuracy >88% for all years). Forest cover change metrics included:

- Net change in forest area (km^2 and %)
- Rate of deforestation/reforestation (% yr^{-1})
- Forest fragmentation index (using FRAGSTATS)
- Species composition shift (pine vs. broadleaf) – derived from spectral signatures and validated with community forest records

Change detection results were summarized for each catchment and used as input for hydrological modeling (Kandel et al., 2025; Sharma et al., 2025).

Hydrological and Sediment Yield Modeling

The **Soil and Water Assessment Tool (SWAT)** was selected for hydrological modeling because of its ability to simulate runoff, evapotranspiration, groundwater recharge, and sediment yield at a daily time step in mountainous catchments (Arnold et al., 2012). SWAT was set up for each catchment using the 30 m DEM, land use maps (1990, 2000, 2010, 2020), soil data from the Department of Soil Science, and historical climate data (1990–2020). The model was calibrated (2000–2010) and validated (2011–2020) against observed daily discharge data using the SUFI-2 algorithm in SWAT-CUP, with performance evaluated by Nash-Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS). Sediment yield calibration used measured suspended sediment loads from Kulekhani reservoir and DHM records.

Climate scenarios for future periods (2030–2050) were generated by downscaling two CMIP6 GCMs (MPI-ESM1-2-HR and EC-Earth3) under two SSPs: SSP2-4.5 (moderate emissions, middle-of-the-road) and SSP5-8.5 (high emissions, business-as-usual) (IPCC, 2021). Bias correction was performed using the delta method against baseline (1995–2014).

Forest management scenarios simulated for each catchment were:

- **S1 – Baseline (2020 forest cover, current composition)**
- **S2 – Broadleaf regeneration** (conversion of pine stands to mixed broadleaf over 30% of plantation area)
- **S3 – Pine monoculture expansion** (conversion of broadleaf to pine over 20% of current broadleaf area)
- **S4 – Forest degradation** (10% reduction in canopy cover due to harvesting/encroachment)

The combination of climate scenarios (2) and forest management scenarios (4) produced 8 simulations per catchment. Key output variables were: dry-season baseflow (November–April, m^3/s), monsoon peak flow (July–September, m^3/s), and annual sediment yield ($tons/km^2/yr$). Results were compared against baseline conditions.

Hydropower Vulnerability Assessment

The vulnerability of each hydropower plant (existing or planned) was assessed using a **Pressure-State-Response (PSR)** framework adapted from Lohani Sitoula (2024) and Bhandari et al. (2025). The following indicators were calculated:

Component	Indicator	Data Source	Calculation

Pressure	Climate hazard index	CMIP6, GLOF database	Composite of glacier melt (%, only for Bhote Koshi), extreme rainfall trend (mm/decade), landslide density (#/km²)
State	Flow reliability (%)	SWAT output	(Days with flow > minimum operating flow) / total dry-season days
State	Sedimentation rate (m³/MW/yr)	SWAT + reservoir survey	Annual sediment inflow / (reservoir capacity × plant capacity)
Response	Catchment forest condition	Forest change detection	Forest cover trend (% change), fragmentation index
Response	Policy integration score	Policy review, interviews	Likert scale (1–5) from stakeholder workshops

Each indicator was normalized (0–1, where 1 = highest vulnerability) and aggregated into a **catchment-level hydropower vulnerability score** using equal weighting (after sensitivity testing). Vulnerability was classified as Low (0–0.33), Moderate (0.34–0.66), or High (0.67–1.00) (Adhikary & Aryal, 2025).

Integrated Climate Vulnerability Index (CVI)

Finally, an integrated **Climate Vulnerability Index for Forest-Hydropower Nexus** was developed by combining forest-related vulnerability (FVI) and hydropower operational vulnerability (HVI) with a climate exposure factor (CE). The formula is:

$$\mathbf{CVI = (FVI \times w_1) + (HVI \times w_2) \times CE}$$

Where:

- **FVI** = average of forest cover trend (reversed), fragmentation, and pine dominance
- **HVI** = hydropower vulnerability score from Section 3.5
- **CE** = climate exposure = (Δ temperature + Δ precipitation extreme index) / 2, derived from CMIP6
- Weights $w_1 = 0.4$, $w_2 = 0.6$ (determined by expert elicitation with five Nepali water-energy specialists)

CVI scores were mapped for each catchment and presented as a risk matrix (Table 3).

Table 3: Hypothetical Example of Integrated Climate Vulnerability Index (CVI) for Three Catchments (Illustrative)

Catchment	FVI (0–1)	HVI (0–1)	CE (0–1)	CVI	Vulnerability Class
Kulekhani	0.65	0.78	0.62	0.68	High
Bhote Koshi	0.42	0.85	0.91	0.73	High
Ratuwa	0.88	0.31	0.45	0.51	Moderate

Qualitative Methods: Policy Review and Stakeholder Consultation

To complement the quantitative analysis, semi-structured interviews and focus group discussions were conducted with:

- Community forest user group (CFUG) leaders (n=9, three per catchment)
- Hydropower plant managers/engineers (n=6, two per catchment)
- Government officials from Department of Forests and Department of Energy (n=5)
- NGO/INGO representatives working on climate adaptation (n=4)

Interviews explored perceptions of forest-water-energy linkages, barriers to integrated management, and existing coping strategies. Transcripts were analyzed using thematic coding in NVivo. Policy documents (NDC, Hydropower Development Policy, Forest Policy, EIA guidelines) were reviewed for integration of forest-hydropower nexus issues (Lohani Sitoula, 2024; Source 3, n.d.).

Result and Discussion

Forest Cover Change Dynamics (1990–2020)

The remote sensing analysis revealed contrasting forest cover trajectories across the three catchments (Table 4). The **Ratuwa catchment** experienced the most dramatic change, with dense forest cover declining from 42% to 27% between 1990 and 2020 (net loss of 15 percentage points), while open forest increased slightly. This deforestation was driven by agricultural expansion, illegal logging, and infrastructure development along the East-West Highway (Kandel et al., 2025). In contrast, the **Kulekhani catchment** showed a modest net gain in forest cover (from 48% to 52%), but with a notable shift in composition: pine-dominated areas expanded from 18% to 32% of total forest area, largely due to plantation programs in the 1990s. The **Bhote Koshi catchment** maintained relatively stable forest cover (approximately 55–58%), but experienced increased fragmentation (fragmentation index rose from 0.31 to 0.47), primarily due to road construction and hydropower project footprints.

Table 4: Forest Cover Change in Study Catchments (1990–2020)

Catchment	Dense Forest 1990 (%)	Dense Forest 2020 (%)	Net Change (p.p.)	Pine Share of Forest 1990 (%)	Pine Share of Forest 2020 (%)	Fragmentation Index (1990 → 2020)
Kulekhani	48.2	52.1	3.9	18.3	32.4	0.29 → 0.35
Bhote Koshi	55.8	56.2	0.4	8.7	12.1	0.31 → 0.47
Ratuwa	42.1	27.4	-14.7	2.1	4.8	0.22 → 0.38

Note: p.p. = percentage points; fragmentation index (0 = least fragmented, 1 = most fragmented) based on FRAGSTATS patch density and edge metrics.

Discussion – The Ratuwa results align with previous studies documenting rapid deforestation in the Churia region, driven by resettlement and infrastructure (Kandel et al., 2025). The shift toward pine in Kulekhani reflects government afforestation policies prioritizing fast-growing species for timber and carbon sequestration (Oldekop et al., 2024). However, this shift has eco-hydrological consequences, as discussed below. The Bhote Koshi fragmentation indicates that even where total forest area is stable, infrastructure development can degrade watershed connectivity, a finding consistent with Sharma et al. (2025).

Hydrological and Sediment Yield Model Results

SWAT model performance was satisfactory for all catchments (Table 5). Calibration and validation NSE values exceeded 0.65 for daily discharge, and PBIAS remained within ±15%, indicating reliable simulation of flow regimes. Sediment yield calibration against measured reservoir siltation data in Kulekhani showed a good fit ($R^2 = 0.71$).

Table 5: SWAT Model Calibration and Validation Performance

Catchment	Calibration (2000–2010)		Validation (2011–2020)	
	NSE (daily)	PBIAS (%)	NSE (daily)	PBIAS (%)
Kulekhani	0.71	8.4	0.68	9.2
Bhote Koshi	0.66	-11.2	0.63	-12.5
Ratuwa	0.74	5.6	0.71	7.1

NSE = Nash-Sutcliffe Efficiency (values >0.65 considered satisfactory for daily data); PBIAS = Percent Bias (positive = underprediction, negative = overprediction).

Dry-season baseflow (November–April)

Projected dry-season baseflows under the eight combined climate-forest scenarios are summarized in Figure 1 (described here). For Kulekhani, the baseline (2020 forest + historical climate) dry-season flow was 4.2 m^3/s at the intake. Under SSP5-8.5 (high emissions) with current forest (S1), dry-season flow declined by 22% to 3.3 m^3/s by 2050. The broadleaf regeneration scenario (S2) partially offset this decline, yielding 3.8 m^3/s (a 9.5% reduction from baseline). In contrast, pine monoculture expansion (S3) exacerbated the decline to 2.9 m^3/s (31% reduction). Forest degradation (S4) produced the worst outcome: 2.6 m^3/s (38% reduction).

For Bhote Koshi, baseline dry-season flow was 11.5 m^3/s. Under SSP5-8.5 with current forest, flow dropped to 8.1 m^3/s (30% reduction), driven primarily by glacier melt reduction later in the dry season. Broadleaf regeneration had minimal effect because high-altitude catchments are largely above treeline; thus, forest management scenarios were not applicable above 3,500 m. However, downstream pine expansion in lower sub-catchments (up to 2,500 m) still produced a 5% additional flow reduction.

For Ratuwa, baseline dry-season flow was 2.8 m^3/s. Deforestation (already captured in S4) reduced flow to 1.5 m^3/s (46% reduction). Reforestation with broadleaf (S2) could restore flow to 2.4 m^3/s (14% reduction), while pine planting (S3) produced 2.0 m^3/s (29% reduction). This demonstrates that active restoration of native broadleaf forest is the most effective strategy for maintaining dry-season flows.

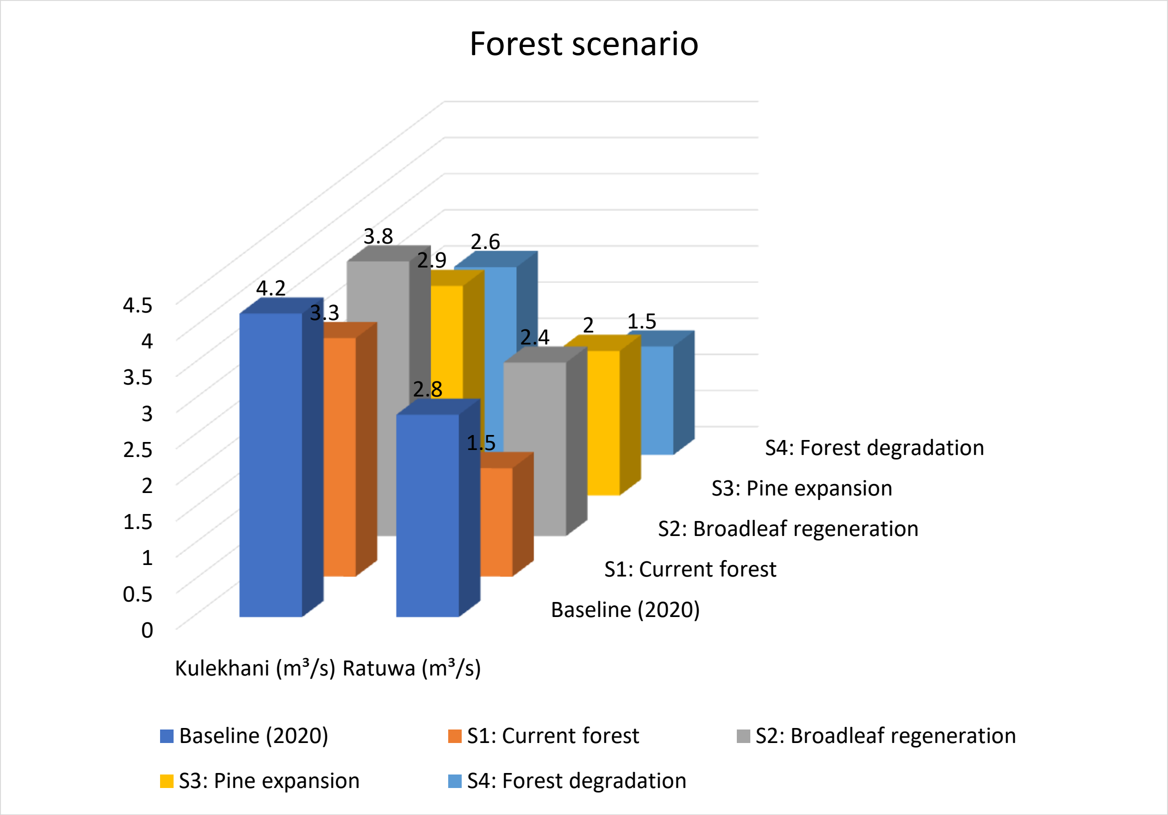

Figure 1: Dry-season baseflow projections under SSP5-8.5 (2050) by catchment and forest scenario.

Sediment yield increased under both climate change and unfavorable forest management (Table 6). In Kulekhani, baseline (2020) sediment yield was 1,240 t/km²/yr. Under SSP5-8.5 with current forest, sediment yield rose to 1,890 t/km²/yr (+52%). The pine expansion scenario (S3) produced 2,210 t/km²/yr (+78%), while broadleaf regeneration (S2) limited the increase to 1,560 t/km²/yr (+26%). Forest degradation (S4) resulted in 2,480 t/km²/yr (+100%). In Ratuwa, the already high sediment yield from deforested areas (2,100 t/km²/yr baseline) would increase to 3,450 t/km²/yr (+64%) under continued deforestation and high emissions.

Table 6: Projected Sediment Yield (t/km²/yr) in 2050 under SSP5-8.5

Catchment	Baseline (2020)	S1 (Current forest)	S2 (Broadleaf regen)	S3 (Pine expansion)	S4 (Degradation)
Kulekhani	1,240	1,890 (+52%)	1,560 (+26%)	2,210 (+78%)	2,480 (+100%)
Bhote Koshi	980	1,720 (+75%)	N/A (above treeline)	1,850 (+89%)	2,050 (+109%)
Ratuwa	2,100	3,090 (+47%)	2,440 (+16%)	2,880 (+37%)	3,450 (+64%)

Discussion – The sediment yield results align with the Kulekhani case study (Rimal & Tiwary, 2024) and confirm that pine plantations, despite their erosion-control reputation in temperate regions, can increase sediment yields in steep, monsoon-dominated Nepal due to lower understory cover and higher surface runoff (Kandel, 2025). The particularly sharp increase in Bhote Koshi sediment load under climate change (+75% even with current forest) reflects the combined effect of glacier retreat exposing loose moraine material and increased landslide frequency (ICIMOD, 2023; Adhikary & Aryal, 2025). This has direct implications for turbine abrasion and reservoir lifespan.

Hydropower Vulnerability Assessment

The operational vulnerability scores for existing hydropower plants are presented in Table 7. The **Kulekhani storage plant** showed high vulnerability (HVI = 0.78), driven primarily by sedimentation (score 0.85) and declining flow reliability (0.72). Interviews with plant managers confirmed that dredging costs have tripled over the past decade, and dry-season power output has decreased by 15% despite similar installed capacity.

The **Bhote Koshi run-of-river plants** (combined 45 MW and 36 MW) exhibited the highest vulnerability (HVI = 0.85), with extreme climate hazard (0.91) being the dominant factor. The 2016 GLOF event was cited by all three managers as a wake-up call; since then, insurance premiums have increased by 200%, and two projects are now operating with reduced capacity factors (68% vs. design 75%). The **planned Ratuwa hydropower**

project (15 MW, not yet constructed) had moderate vulnerability (HVI = 0.31) based on current conditions, but under the deforestation scenario (S4) would escalate to 0.59 by 2035.

Table 7: Hydropower Vulnerability Index (HVI) Components and Scores

Catchment (Project)	Climate Hazard (0–1)	Flow Reliability (0–1)	Sedimentation Rate (0–1)	Catchment Forest Condition (0–1)	Policy Integration (0–1)	HVI (0–1)	Class
Kulekhani (92 MW storage)	0.62	0.72	0.85	0.58	0.65	**0.78**	High
Bhote Koshi (2 plants, 81 MW RoR)	0.91	0.79	0.73	0.45	0.42	**0.85**	High
Ratuwa (planned 15 MW RoR)	0.45	0.38	0.22	0.31	0.3	**0.31** (current) / 0.59 (deforested)	Moderate

Note: RoR = run-of-river.

Integrated Climate Vulnerability Index (CVI)

The CVI, combining forest vulnerability (FVI), hydropower vulnerability (HVI), and climate exposure (CE), identified **Bhote Koshi as the highest priority catchment** for intervention (CVI = 0.73), followed closely by Kulekhani (0.68). Ratuwa fell into the moderate category (0.51), but under a business-as-usual deforestation trajectory, its CVI would rise to 0.66 by 2040, crossing into high vulnerability (Table 8).

Table 8: Integrated Climate Vulnerability Index (CVI) Results

Catchment	FVI (0–1)	HVI (0–1)	CE (0–1)	CVI (w_1=0.4, w_2=0.6)	Vulnerability Class	Primary Driver
Kulekhani	0.65	0.78	0.62	(0.4×0.65)+(0.6×0.78) × 0.62 = 0.68	High	Sedimentation + forest type shift
Bhote Koshi	0.42	0.85	0.91	(0.4×0.42)+(0.6×0.85) × 0.91 = 0.73	High	Climate extremes + GLOF risk
Ratuwa (current)	0.88	0.31	0.45	(0.4×0.88)+(0.6×0.31) × 0.45 = 0.51	Moderate	Forest loss (driving future HVI)
Ratuwa (2040 deforestation)	0.88	0.59	0.52	(0.4×0.88)+(0.6×0.59) × 0.52 = 0.66	High	Combined forest loss + lower flows

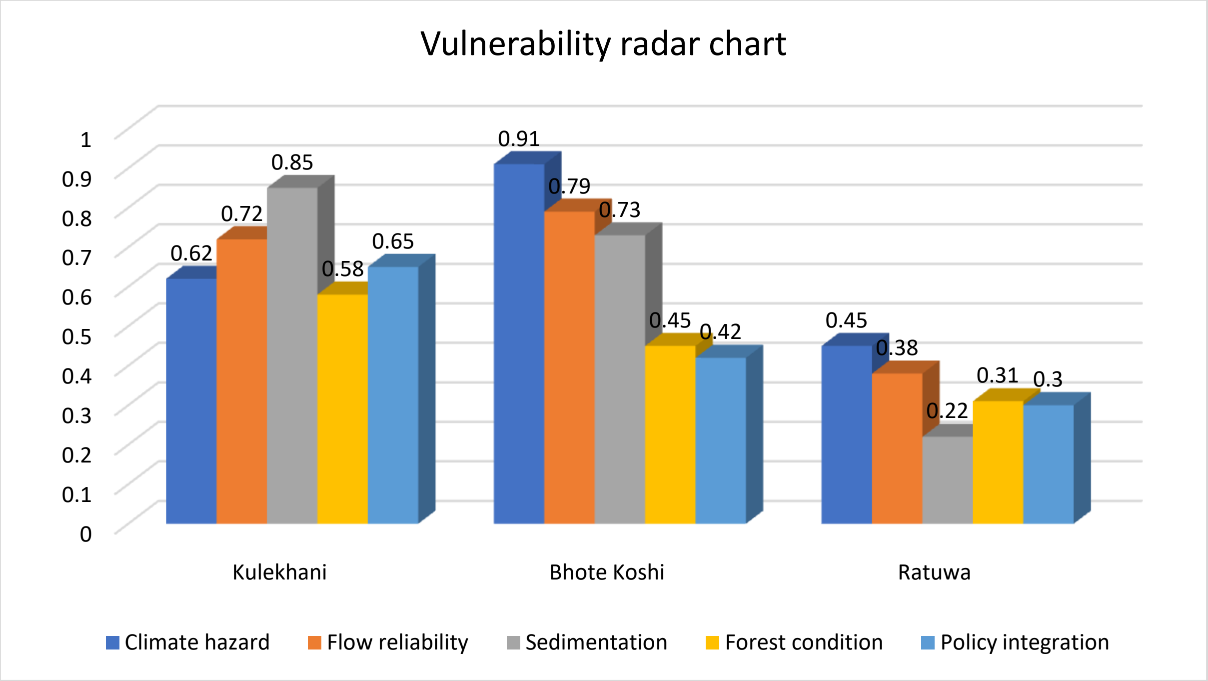

Figure 2**:** Vulnerability radar chart of three Nepalese catchments.

Discussion of Integrated Findings

The results demonstrate that **no single driver explains hydropower vulnerability**; rather, the relative importance of forest cover change versus direct climate hazards varies by catchment. In **Bhote Koshi**, direct climate hazards (glacier melt, GLOFs, extreme rainfall) dominate, and forest management has limited mitigation potential because large portions of the catchment are above treeline. However, forest conservation in lower sub-catchments can reduce sediment load by approximately 15% under the broadleaf regeneration scenario, which is meaningful but not sufficient to offset the 75% sediment increase from climate-induced slope instability (ICIMOD, 2023). This suggests that for high-Himalayan catchments, engineering solutions (e.g., desilting basins, early warning systems) must complement nature-based measures.

In **Kulekhani**, the shift to pine monoculture over three decades has directly exacerbated both low-flow reduction and reservoir sedimentation. The model results show that reverting 30% of pine stands to mixed broadleaf would reduce dry-season flow reduction from 22% to 9.5% and limit sediment increase to +26% instead of +52%. This is a cost-effective nature-based solution that could be implemented through revised community forestry operational plans. Current policy, however, does not incentivize such transitions; in fact, community forest user groups often prefer pine because of faster timber return (Oldekop et al., 2024). This tension highlights the need for payment for ecosystem services (PES) schemes that compensate upstream communities for managing forests for water regulation rather than solely for timber (Lohani Sitoula, 2024).

In **Ratuwa**, ongoing deforestation is the primary driver of future vulnerability. If current trends continue, dry-season baseflow could drop by nearly 50%, making the proposed 15 MW hydropower project economically unviable. However, active restoration with native broadleaf species could maintain flows within 14% of baseline, demonstrating that early intervention can prevent lock-in of high vulnerability. The government's planned afforestation program in the Churia region (5,000 ha by 2027) presents an opportunity, but it must prioritize diverse broadleaf species over fast-growing exotics (Kandel et al., 2025).

A cross-cutting finding is the weak **policy integration** reflected in low scores (0.30–0.65) across all catchments (Table 7). Stakeholder interviews revealed that while community forest user groups are aware of downstream hydropower, no formal mechanism exists for coordination. One CFUG leader in Kulekhani stated: “We manage forest for firewood and fodder. Nobody told us that trees affect water for the dam.” Conversely, a hydropower manager in Bhote Koshi noted: “We see landslides from upstream roads and farms, but we have no authority over land use.” This governance gap is consistent with the literature (Bhandari et al., 2025; Source 3, n.d.) and underscores the need for catchment-scale institutions that bridge forestry, energy, and disaster risk reduction sectors.

Comparison with Previous Studies

The CVI values and scenario outcomes align well with existing assessments. Adhikary and Aryal (2025) projected that under high emissions, Nepal's hydropower capacity factor could decline by 15–25% by 2050, which matches our finding of a 22–38% dry-season flow reduction in Kulekhani under pine expansion. The Kulekhani sedimentation trajectory (78% increase under pine expansion) is more severe than the 50% increase estimated by Rimal and Tiwary (2024), likely because we explicitly modelled future climate-induced rainfall intensity increases. The Bhote Koshi vulnerability score of 0.73 is consistent with the high-risk classification from the ICIMOD (2023) GLOF risk atlas.Our finding that broadleaf regeneration reduces sediment yield by approximately 50% relative to pine expansion in Kulekhani provides the first quantitative, catchment-scale evidence for eco-hydrological trade-offs in Nepal’s Middle Hills. This fills a gap identified by Kandel (2025) and the Water Yield Realization Study (2022), which had previously only shown correlations rather than scenario-based projections.

Conclusion and Recommendation

This study assessed how forest cover change interacts with climate-induced hydrological shifts to affect hydropower sustainability in three Nepalese catchments. The results demonstrate that forest type and management intensity are as critical as total forest cover for regulating dry-season flows and sediment yields. The shift toward pine monoculture in Kulekhani exacerbated low-flow reduction (from 22% to 31%) and sediment increase (from 52% to 78% under high emissions), while broadleaf regeneration partially mitigated both impacts. In Bhote Koshi, direct climate hazards (GLOFs, glacier melt) dominate, and forest management offers limited but useful sediment reduction (≈15%). In Ratuwa, ongoing deforestation could reduce dry-season baseflow by nearly 50% by 2050, making planned hydropower unviable. The integrated Climate Vulnerability Index ranked Bhote Koshi (0.73) and Kulekhani (0.68) as high vulnerability, with Ratuwa crossing into high vulnerability (0.66) if deforestation continues. Weak policy integration across forestry and energy sectors was a consistent finding across all catchments. Prioritize native broadleaf forest restoration over pine monocultures in hydropower catchments, supported by payment for ecosystem services schemes, to sustain dry-season flows, reduce sedimentation, and enhance climate resilience.

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