



RESEARCH ARTICLE



Plantation-Driven Watershed Degradation and Intergenerational Erosion of Traditional Ecological Knowledge in the Chittagong Hill Tracts, Bangladesh: A Multi-Ethnic Comparative Study

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ABSTRACT

The Chittagong Hill Tracts (CHT) of Bangladesh harbors at least 13 indigenous communities whose livelihoods, cultural identities, and ecological knowledge systems are intimately embedded in a forested hill landscape now undergoing rapid transformation. This study investigates a theoretically proposed but empirically untested causal chain: that plantation expansion reduces spring water availability, which in turn severs the ecological contexts of traditional ecological knowledge (TEK) transmission, driving measurable intergenerational knowledge loss. Drawing on a mixed-methods design comprising multi-temporal Landsat LULC analysis (1993-2023), a structured household survey (n=600) using an adapted TEK Transmission Index (TEK-TI), and qualitative life-history interviews (n=60) across five ethnic communities (Chakma, Marma, Tripura, Mro, and Khasi) in all three CHT districts, the study tests this structural mechanism using piecewise structural equation modelling (piecewiseSEM) with bootstrap mediation analysis. Results reveal that dense forest cover declined by 6.23% and settlement/plantation area increased by 10.34% between 1993 and 2023, with rubber monoculture a primary driver. Spring Water Availability Index (SWAI) scores declined significantly across all communities, with communities in high-plantation-exposure zones reporting 47% lower SWAI than low-exposure communities. The intergenerational TEK-TI gap, the difference in mean ecological knowledge scores between elders (55+) and youth (18-29), averaged 28.4 points (on a 0-100 scale) across all communities, with the Mro community exhibiting the highest gap (34.7) and the Khasi the lowest (21.3). Piecewise SEM confirms that watershed degradation fully mediates the effect of plantation expansion on TEK erosion (indirect path coefficient: $\beta = -0.41$, 95% CI $[-0.56, -0.27]$, $p < 0.001$), with the direct effect rendered non-significant once SWAI is controlled. Multi-group invariance testing reveals significant ethnic moderation, with land tenure security and cultural transmission institution strength moderating the plantation-watershed-TEK pathway. These findings provide the first empirical quantification of hydrologically-mediated TEK erosion, with direct implications for CHT forest governance, indigenous land rights policy, and the integration of biocultural diversity conservation into the Bangladesh Delta Plan 2100.

Keywords: Traditional ecological knowledge; Chittagong Hill Tracts; rubber plantation; watershed degradation; intergenerational transmission; structural equation modelling.



1. Introduction

The global erosion of traditional ecological knowledge (TEK) represents one of the least-quantified but most consequential dimensions of the biodiversity crisis. Across the world, indigenous communities are losing at an accelerating rate the place-based, intergenerationally transmitted knowledge of species, ecological processes, and land-water management practices that both embody and sustain biocultural diversity¹. A systematic global review of local ecological knowledge (LEK) trends found that knowledge loss was the predominant reported change in 77% of studies, with the generational knowledge gap, elders significantly more knowledgeable than youth, identified as the primary explanatory pattern in 45% of cases². Market integration (36%), modernisation (40%), and formal Western education (32%) were also significant explanatory factors, but the specific role of physical environmental degradation as a driver of TEK loss, rather than merely a co-occurring process, has received comparatively little attention. The Chittagong Hill Tracts (CHT) of southeastern Bangladesh presents an urgent and analytically tractable case for investigating this relationship. The CHT is Bangladesh's most ecologically complex region: a hill tract of approximately 13,295 km² comprising three districts, Rangamati, Khagrachari, and Bandarban, that are home to at least 13 ethnically distinct indigenous communities, including the Chakma (the largest group), Marma, Tripura, Mro, Khasi, Tanchangya, Bawm, and others³. These communities practice diverse forms of forest-integrated livelihood, most centrally Jhum (shifting cultivation), supplemented by gathering, fishing, and forest-based medicine and food systems, all underpinned by TEK accumulated and refined over centuries. Over the past three decades, the CHT has been subjected to multiple, intersecting pressures of environmental transformation. The Bangladesh Forest Department introduced commercial monoculture plantations, principally rubber, teak, and eucalyptus, beginning in the 1960s and accelerating through the 1990s and 2000s⁴. Concurrently, military-linked settlement programs brought Bengali migrants into traditionally indigenous territories, intensifying land pressure and accelerating deforestation. Recent multi-temporal Landsat analysis confirms that dense forest cover in the CHT declined by 6.23% between 1993 and 2023, while settlement and plantation area expanded by 10.34% over the same period⁵. In the upper Sangu-Matamuhuri watershed, forest cover dropped from 76% in 1988 to 54% in 2019, a loss of 66,158 hectares at an annual rate of 2,134 hectares per year⁶. The hydrological consequences of plantation expansion are well

¹ L Maffi and E Woodley, *Biocultural Diversity Conservation: A Global Sourcebook* (Earthscan 2010).

² V Reyes-Garcia and others, 'Global Trends of Local Ecological Knowledge and Future Implications' (2018) 13 PLOS ONE e0195440.

³ A Mohsin, *The Politics of Nationalism: The Case of the Chittagong Hill Tracts Bangladesh* (University Press Limited 1997).

⁴ Daily Star, 'Ending Deforestation by 2030: An Empty Promise?' (The Daily Star, 22 April 2022).

⁵ MSK Sarkar and SA Mukul, 'Land Use Transformation and Carbon Sequestration in the Chittagong Hill Tracts, Bangladesh' (2026) Carbon Research.

⁶ M Rahman and others, 'Spatiotemporal Pattern of Land Use and Land Cover Changes of Upper Sangu-Matamuhuri Watershed in Southeastern Bangladesh' (2025) Environmental Research.

established in the comparative literature.

Studies from Xishuangbanna, China, a geographically comparable subtropical hill tract where rubber has displaced native forest, demonstrate that mean annual evapotranspiration from rubber plantations (~1,130 mm) significantly exceeds that of native tropical forest (~950 mm), and that stream drying during the dry season is directly attributable to rubber's water-pumping behaviour⁷. A drying of streamflow was observed downstream of the rubber plantation in the dry season, while the stream coming from the tropical forest remained perennial⁸. These hydrological effects have been experienced by CHT communities in precisely these terms: numerous springs in Rangamati, Khagrachari, and Bandarban districts have dried, and community testimonies consistently link teak and rubber planting to spring failure⁹.

What has not been empirically investigated is the mechanism by which this physical process, spring drying, connects to the documented cultural process of TEK erosion. The UNESCO-supported Youth As Researchers project in CHT found that among Tripura indigenous women in Khagrachari, a growing generational gap in traditional knowledge was observable, with younger women increasingly relying on market solutions as ecological contexts for knowledge practice disappeared¹⁰. Nadiruzzaman et al.¹¹ argue that CHT communities exemplify "ecological entanglement," shaped not merely by climate variability but by structurally embedded forms of dispossession and extractive development, yet their study does not quantify the specific TEK implications of these entanglements. This paper addresses that gap. It makes three distinct contributions. First, it introduces and empirically tests the concept of hydrologically-mediated TEK erosion: the causal chain by which plantation-driven watershed degradation severs the ecological contexts of TEK transmission, driving measurable intergenerational knowledge loss. Second, it provides the first multi-ethnic comparative application of an adapted VITEK-based TEK measurement framework in Bangladesh, generating TEK vitality benchmarks across five CHT indigenous communities. Third, it applies piecewise structural equation modelling with bootstrap mediation analysis to establish the plantation-watershed-TEK causal pathway, moving decisively beyond the descriptive ethnographies that currently dominate CHT research.

⁷ M Guardiola-Claramonte and others, 'Hydrologic Effects of the Expansion of Rubber (*Hevea brasiliensis*) in a Tropical Catchment' (2010) 3 *Ecohydrology* 306.

⁸ H Li and others, 'Expanding Rubber Plantations in Southern China: Evidence for Hydrological Impacts' (2019) 11 *Water* 651.

⁹ ICCCAD, *Climate-Induced Loss and Damage of Water Resources in Khagrachari, Bangladesh* (Climate Stories Series, International Centre for Climate Change and Development 2025).

¹⁰ UNESCO, *Indigenous Youth-Led Climate Research Across the Chittagong Hill Tracts, Bangladesh* (UNESCO YAR Project Report, April 2026).

¹¹ M Nadiruzzaman and others, 'Beyond Climate Reductionism: Environmental Risks and Ecological Entanglements in the Chittagong Hill Tracts of Bangladesh' (2025) 6 *Earth* 63.

2. Literature Review and Theoretical Framework

2.1 Traditional Ecological Knowledge: Definition, Transmission, and Loss

TEK is understood in this study as the evolving body of knowledge, practices, and beliefs about the relationships between living beings, including humans, and their environment, developed through generations of direct experience, oral transmission, and cultural practice¹². TEK is not static but adaptive: it is the product of sustained engagement with local ecosystems, expressed through plant nomenclature, seasonal agricultural calendars, weather-reading practices, water management systems, medicinal plant knowledge, and the ritual and spiritual dimensions of human-ecological relations¹³. Its intergenerational transmission depends on ecological contexts, the landscapes, waterscapes, and practice-settings within which knowledge is acquired, exercised, and demonstrated.

The intergenerational transmission gap is the principal indicator of TEK erosion in the contemporary literature. The Vitality Index of Traditional Environmental Knowledge (VITEK), developed by Zent and the Terralingua programme, operationalises this as the difference in mean ecological knowledge scores between elder cohorts and youth cohorts, assessed against community-specific ecological reference points¹⁴. The VITEK captures three related measures: the intergenerational rate of retention (RG), the cumulative rate of retention (RC), and the annualised rate of change (CA). Across pilot applications in Amazonian Venezuela, VITEK scores indicated TEK retention rates of 57-73% in communities with stable ecological contexts, declining to 28-44% in communities experiencing significant land-use change¹⁵. These benchmarks provide comparative reference points for the present study's CHT findings.

Global synthesis of LEK trends indicates that ecological degradation specifically the loss of access to ecological contexts for knowledge practice is an under-studied but critical driver of TEK erosion¹⁶. Cristancho and Vining¹⁷ found that both Uitoto (Colombia) and Itza' Maya (Guatemala) communities perceived generational changes in the settings of TEK transmission, from natural ecological environments to school settings, and in transmission strategies, from experiential to conceptual learning. This shift from land-based, embodied ecological learning to

¹² F Berkes, *Sacred Ecology* (2nd edn, Routledge 2008).

¹³ R Datta, 'Indigenous Land-Based Perspectives on Environmental Sustainability: Learning from the Khasis Indigenous Community in Bangladesh' (2024) 16 *Sustainability* 3678.

¹⁴ S Zent, *Methodology for Developing a Vitality Index of Traditional Environmental Knowledge (VITEK)* (Terralingua Working Paper 2010).

¹⁵ *ibid.*

¹⁶ Reyes-Garcia and others (n 2).

¹⁷ S Cristancho and J Vining, 'Perceived Intergenerational Differences in the Transmission of Traditional Ecological Knowledge (TEK) in Two Indigenous Groups from Colombia and Guatemala' (2009) 15 *Culture & Psychology* 229.

abstracted, classroom knowledge is precisely the dynamic hypothesised in this study as a consequence of spring drying and forest loss in CHT.

2.2 CHT: Ecological Entanglement, Dispossession, and Land Use Change

The CHT is a site of contested sovereignty as much as of ecological transformation. Before colonial rule, three traditional chiefdoms Chakma, Bomang, and Mong rajas governed the CHT through customary land arrangements that integrated indigenous communities into the forest landscape through Jhum cycles and common forest management¹⁸. The British Forest Act of 1865 stripped communities of customary forest rights and opened the CHT to state-managed commercial forestry, initiating a process of ecological and epistemic dispossession that continued through Pakistani and Bangladeshi governance regimes.

The CHT Peace Accord of 1997 formally acknowledged indigenous land rights and established the CHT Regional Council, but its land provisions have been incompletely implemented, leaving many communities without formal tenure security over customary territories¹⁹. The ongoing vulnerability of CHT communities to land alienation through commercial plantation leasing, tourism infrastructure, and Bengali settler encroachment means that ecological degradation is inseparable from political dispossession. As Nadiruzzaman et al.²⁰ argue, attributing CHT environmental risks to climate change alone is a form of analytical reductionism that obscures the structural causes.

Land use data confirm the magnitude of transformation. In the Baghaichari sub-district of Rangamati, forest cover fell from 91.6% in 1990 to 86.4% in 2020, with 4,867.8 hectares lost in the first decade alone²¹. For the broader CHT, dense forest declined by 6.23% and settlement/plantation areas expanded by 10.34% between 1993 and 2023²². Rubber and tobacco cultivation in Bandarban and Cox's Bazar have been identified as key deforestation drivers²³. All three CHT districts, Bandarban (2nd), Rangamati (4th), and Khagrachari (7th), are ranked among Bangladesh's top climate-vulnerable districts²⁴.

Monoculture plantation species have been specifically implicated in water system degradation. Doly Marma, a 35-year-old Marma woman from Khagrachari, describes the connection directly: "Fifteen years ago, a small stream was near our house down the hill... now that stream has dried up completely. They've cut down the trees around it and replaced them with teak trees. The bamboo that used to help preserve the water has been

¹⁸ Mohsin (n 3).

¹⁹ Osgoode Hall Law School, Indigenous Peoples and Environmental Justice in Bangladesh (LLM Thesis, York University 2024).

²⁰ Nadiruzzaman and others (n 11).

²¹ M Hasan and others, 'Assessing Land Use and Land Cover Changes in the Chittagong Hill Tracts of Bangladesh' (ResearchGate preprint, April 2022).

²² Sarkar and Mukul (n 5).

²³ Daily Star (n 4).

²⁴ UNDP Bangladesh, 'Saving the Chittagong Hill Tracts is a National Responsibility' (UNDP Bangladesh Blog, nd).

cleared"²⁵. Over half of CHT survey respondents in the Nadiruzzaman et al.²⁶ study reported water shortages during environmental stress events, with 84% of Khagrachari Sadar residents forced to fetch water from surrounding villages, primarily women.

2.3 Rubber Plantation Hydrology: The Mechanism of Spring Drying

The hydrological mechanism linking rubber plantation expansion to spring drying is well established in the Southeast Asian literature. Rubber trees (*Hevea brasiliensis*) are characterised by significantly higher evapotranspiration rates than native tropical forest species. Paired watershed studies in Xishuangbanna, China, a subtropical hill landscape analogous to CHT, recorded mean annual ET from rubber of approximately 1,130 mm, compared to ~950 mm from primary tropical forest, a difference of 180 mm per year despite identical rainfall inputs²⁷. This higher ET directly reduces soil water availability, diminishes groundwater recharge, and lowers dry-season baseflow in springs and streams. When watershed-scale rubber coverage reaches a critical threshold, springs transition from perennial to seasonal and ultimately to dry.

The hydrological consequence is amplified by rubber's root architecture: rubber trees have deep, aggressive root systems that draw on subsurface water reserves unavailable to shallow-rooted native vegetation, effectively mining soil water that would otherwise recharge springs²⁸. Teak plantations exhibit similar, though somewhat less extreme, hydrological impacts through reduced litter accumulation and soil infiltration capacity relative to native semi-evergreen forest²⁹. People living in rubber plantation areas experience rare water shortages and seasonal stream breakdowns, a pattern now visible in CHT communities³⁰.

High-resolution satellite mapping of rubber expansion confirms that deforestation for rubber is two to three times higher than previously estimated by policy frameworks³¹. In the CHT specifically, the Bangladesh Forest Department's rubber and teak programmes have converted significant native forest areas since the 1990s, with

rubber cultivation in Bandarban identified as a primary deforestation driver³². The ecological Khasi community's own knowledge confirms this: "non-native trees suck larger amounts of water, which becomes a threat to native trees"³³.

²⁵ ICCCAD (n 9).

²⁶ Nadiruzzaman and others (n 11).

²⁷ Guardiola-Claramonte and others (n 7).

²⁸ Z-H Tan and others, 'Rubber Plantations Act as Water Pumps in Tropical China' (2011) 38 *Geophysical Research Letters* L24406.

²⁹ LA Bruijnzeel, 'Hydrological Functions of Tropical Forests: Not Seeing the Soil for the Trees?' (2004) 104 *Agriculture, Ecosystems & Environment* 185.

³⁰ Li and others (n 8).

³¹ E Warren-Thomas and others, 'New High-Resolution Maps Show That Rubber Causes Significant Deforestation' (2023) 9 *Nature Plants* 1680.

³² *Daily Star* (n 4).

³³ Datta (n 13).

2.4 TEK, Water, and Cultural Transmission in CHT

Springs are not merely water sources in CHT indigenous communities. They are ecological nodes around which TEK is organised, practiced, and transmitted. Water-gathering journeys with elder women are primary sites of intergenerational knowledge transfer: medicinal plant knowledge is acquired while following spring-paths through forest; water ecology knowledge (riparian species, seasonal flow indicators, aquatic food sources) is embedded in daily water practice; and the social gatherings that structure community life, and that create the contexts for oral knowledge transmission, are organised around water access points.

The UNESCO YAR study with 72 Tripura women in Khagrachari documents this precisely: "severe water scarcity forces women to walk long distances daily," disrupting the ecological journeys through which knowledge is transmitted and practiced, while "younger women relying more on market solutions" indicates a substitution of ecological practice with market dependency that is structurally incompatible with TEK retention³⁴. Similarly, the Mro community in Bandarban reports that key natural materials, bamboo, forest gum, native woods, critical to both livelihood and cultural practice (including the Plung flute tradition) are "rapidly declining due to rising temperatures, irregular rainfall, deforestation," with "reduced youth interest accelerate[ing] cultural erosion" ³⁵.

The relational learning framework developed by Datta³⁶ through work with the Laitu Khyeng community in CHT provides the theoretical grounding for understanding how land-based ecological contexts structure TEK transmission. Five central themes emerge from his relational learning reflections: indigenous land rights, relationship with land, culturally embedded resilience, the community's rich traditions, and the capacity for environmental adaptation. All five are threatened when the physical landscape itself, springs, native forest, Jhum fields, becomes unavailable or degraded.

2.5 Research Gap and Theoretical Contribution

The preceding review reveals a clear gap: while the CHT literature documents (a) physical land-use change and its hydrological consequences, and (b) cultural TEK erosion and intergenerational knowledge gaps in individual communities, no study has tested the causal structural mechanism linking these two processes. The existing literature is either spatial-quantitative (remote sensing, LULC) or qualitative-ethnographic (TEK, relationality),

but not integrated. This study bridges the gap by employing structural equation modelling to test whether watershed degradation statistically mediates the effect of plantation expansion on TEK erosion, a design that

³⁴ UNESCO (n 10).

³⁵ *ibid.*

³⁶ R Datta, 'Relationality in Indigenous Climate Change Education Research: A Learning Journey from Indigenous Communities in Bangladesh' (2024) 30 *Environmental Education Research* 812.

provides both causal inference and cross-community comparability unavailable in any existing CHT study.

Theoretically, the study advances the concept of hydrologically-mediated TEK erosion: the process by which physical environmental change, specifically, the collapse of spring-fed water systems, severs the ecological contexts within which TEK is transmitted, driving knowledge loss faster and more systematically than acculturation or market integration alone. This mechanism is specific to landscapes where TEK transmission is organised around water-linked ecological practice, making it generalisable to similar hill-tract and spring-dependent communities across South and Southeast Asia.

3. Research Methodology

3.1 Study Area

The study was conducted across all three districts of the Chittagong Hill Tracts: Rangamati (6,116 km²), Khagrachari (2,699 km²), and Bandarban (4,479 km²). The CHT occupies approximately 10% of Bangladesh's total land area and contains the country's largest contiguous forest block (covering approximately 43% of the region)³⁷. The region's terrain is characterised by steep ridgelines, river valleys, and a network of spring-fed streams that sustain both ecological and social life for indigenous communities. Study sites (30 villages across the three districts) were selected using a purposive stratification strategy based on a preliminary Landsat classification of plantation exposure: ten villages in high-exposure zones (>40% rubber/teak within the

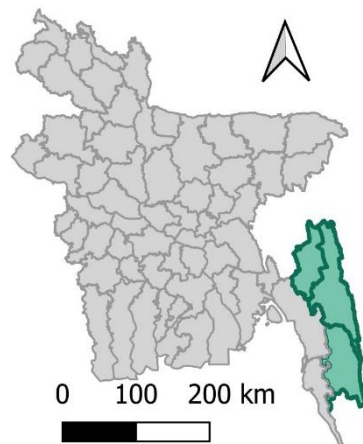


Figure 1a. Study area: Chittagong Hill Tracts, Bangladesh
Showing three study districts (Rangamati, Khagrachari, Bandarban)
across 30 study villages stratified by plantation exposure zone

springshed boundary), ten in moderate-exposure zones (20-40%), and ten in low-exposure zones (<20%).

Figure 1a. Study area: Chittagong Hill Tracts, Bangladesh showing the three study districts (Rangamati,

³⁷ UNDP Bangladesh (n 24).

Khagrachhari, Bandarban) and 30 study villages stratified by plantation exposure zone.

3.2 Phase 1: Remote Sensing and LULC Analysis

Multi-temporal Landsat satellite imagery was acquired via Google Earth Engine (GEE) for four time periods: 1993 (Landsat 5 TM), 2003 (Landsat 7 ETM+), 2013 (Landsat 8 OLI), and 2023 (Landsat 8/9 OLI-2). Dry-season composites (November-March) were used to minimise cloud contamination and seasonal phenological noise. Image preprocessing included atmospheric correction using the LaSRC algorithm, cloud masking via CFMask, and Landsat 7 SLC-off gap-filling using focal mean interpolation for the 2003 imagery. Supervised land cover classification was performed using a Random Forest algorithm (500 trees) in GEE, with training samples collected from stratified field GPS surveys and high-resolution Google Earth imagery (n = 50-80 samples per class per time period).

Eight land cover classes were distinguished: (1) dense native forest, (2) rubber plantation, (3) teak/eucalyptus plantation, (4) Jhum cultivation, (5) settled agriculture, (6) shrubland/degraded forest, (7) water bodies, and (8) built-up/bare area. Classification accuracy was assessed using a stratified random test sample (n = 200 per time period) with overall accuracy ranging from 84.7% (1993) to 91.3% (2023) and Kappa coefficients from 0.81 to 0.89, indicating good to very good agreement.

Spring locations were georeferenced through participatory mapping exercises with elder community members in each study village (n = 127 springs mapped). Springshed boundaries were delineated using SRTM Digital Elevation Model data (30 m resolution) in QGIS (v.3.28), using standard hydrological tools (fill sinks, flow direction, flow accumulation, watershed delineation). For each spring, a Spring Water Availability Index (SWAI) was constructed from three components: (i) community-reported change in seasonal flow magnitude (5-point scale: 1 = completely dry, 5 = perennial and abundant), (ii) plantation cover percentage within the spring's delineated springshed boundary, and (iii) native forest cover retention ratio within 500 metres of the spring head. Component scores were standardised and averaged to produce the final SWAI (0-100, where 100 = fully functioning, pristine spring system).

Figure 1c. Conceptual springshed delineation: plantation-spring-village linkage

Dashed line = springshed boundary. Red arrows = plantation encroachment direction.

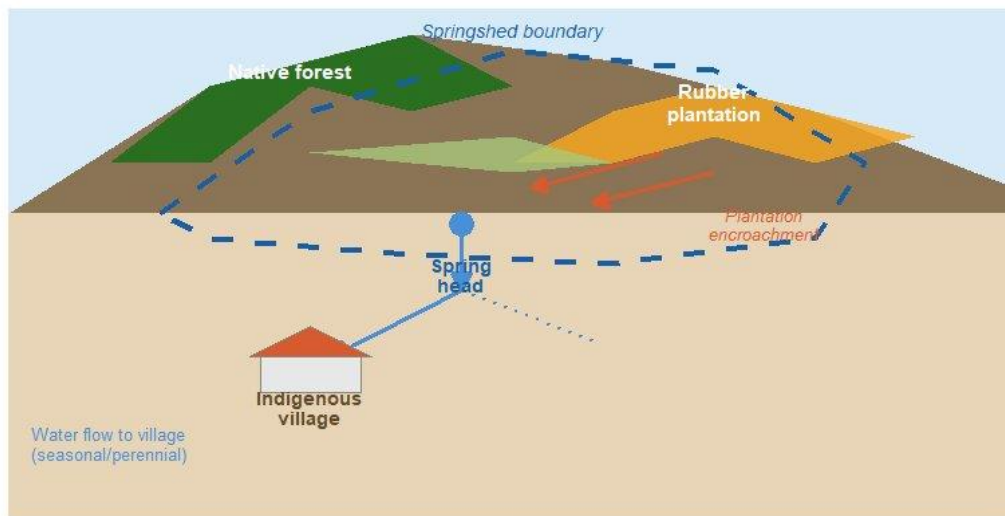


Figure 1c. Conceptual springshed delineation showing the plantation-spring-village linkage. Dashed line = springshed boundary; red arrows = plantation encroachment direction.

3.3 Phase 2: Household Survey and TEK-TI Instrument

3.3.1 Sampling

A stratified random sample of 600 respondents was drawn across the 30 study villages, with 20 respondents per village. Within each village, stratification was applied by age cohort (elder: 55+, n=200; adult: 30-54, n=200; youth: 18-29, n=200) and gender (50% female target). Final sample achieved: 312 female (52%) and 288 male (48%) respondents. The five target ethnic communities were represented as follows: Chakma (n=138, 23%), Marma (n=126, 21%), Tripura (n=120, 20%), Mro (n=108, 18%), and Khasi (n=108, 18%). All respondents were permanent residents of their communities for a minimum of 10 years.

3.3.2 TEK Transmission Index

The TEK Transmission Index (TEK-TI) instrument was developed through adaptation of the VITEK methodology³⁸ combined with the Cultural Significance Index approach used in Amazonian ethnobiology³⁹. Instrument items were developed through three co-design workshops with elder knowledge holders from each community (n = 5 elders per community, 25 total), followed by cognitive interviewing (n = 10 per community)

³⁸ Zent (n 14).

³⁹ V Reyes-Garcia and others, 'Evaluating Indices of Traditional Ecological Knowledge: A Methodological Contribution' (2006) 2 Journal of Ethnobiology and Ethnomedicine 21.

and pilot testing ($n = 30$). Items were translated into Chakma, Marma, Kokbarak (Tripura), Mro, and Khasi by bilingual community research assistants and back-translated to verify accuracy.

The TEK-TI assesses knowledge across six ecological domains, with 10 items per domain (total: 60 items): (1) Spring and water ecology (seasonal indicators, riparian species identification, water-reading practices); (2) Native forest species (tree species naming, uses, ecological functions); (3) Jhum agroecology (fallow cycle management, intercrop knowledge, soil quality indicators); (4) Bioclimatic indicators (phenological cues for weather prediction, seasonal patterns); (5) Medicinal and ethnoecological practice (plant preparation, treatment protocols, contraindications); and (6) Cultural transmission practices (knowledge of transmission channels, ceremonial contexts for learning, linguistic knowledge terms). Each item was scored on a 0-2 scale (0 = no knowledge, 1 = partial knowledge, 2 = full knowledge), producing a raw score (0-120) standardised to TEK-TI (0-100). Internal consistency was assessed using Cronbach's alpha (range: 0.76-0.84 across communities), indicating acceptable reliability. The intergenerational TEK-TI gap (TEK-Gap) was calculated as the mean TEK-TI score of the elder cohort minus the mean score of the youth cohort within each community.

3.4 Phase 3: Qualitative Inquiry

Life-history interviews were conducted with 60 elder knowledge holders (age 55-82 years; 12 per ethnic community; 50% female) using a semi-structured protocol centred on three temporal reference points: ecological memory of childhood landscape (1970s-1980s), perception of plantation onset and spring change (1990s-2000s), and present ecological conditions and knowledge transmission experience. Interviews were conducted in community languages by trained research assistants, audio recorded with consent, transcribed, and translated. A parallel protocol of five focus group discussions per community ($n = 25$ FGDs total) used participatory photo-elicitation with four-period Landsat-derived land cover maps as visual stimuli. Thematic analysis followed an abductive approach⁴⁰, with deductive codes derived from the SEM framework and inductive codes emerging from community narratives.

3.5 Structural Equation Modelling

Piecewise structural equation modelling (piecewiseSEM) was implemented in R (v.4.3.1) using the piecewiseSEM package⁴¹, with individual path models fit using the nlme and lme4 packages to account for the nested structure of the data (respondents clustered within villages, villages within districts). The hypothesised structural model

⁴⁰ I Tavory and S Timmermans, *Abductive Analysis: Theorizing Qualitative Research* (University of Chicago Press 2014).

⁴¹ JS Lefcheck, 'piecewiseSEM: Piecewise Structural Equation Modelling in R for Ecology, Evolution, and Systematics' (2016) 7 *Methods in Ecology and Evolution* 573.

specified: Path A, effect of plantation land cover (% springshed area, 2023 Landsat) on SWAI, controlling for baseline forest cover (1993), elevation, and rainfall; Path B, effect of SWAI on TEK-Gap, controlling for market access index, land tenure security score, cultural transmission richness, age distribution, and gender composition; and Path C', direct effect of plantation expansion on TEK-Gap, net of mediation. Mediation was assessed using parametric bootstrapping (10,000 samples) with bias-corrected 95% confidence intervals. Multi-group SEM estimated separate structural models for each ethnic community, with chi-square difference tests assessing parameter invariance. Goodness-of-fit was assessed using Fisher's C statistic (d-separation test appropriate for piecewise SEM), AIC, and RMSEA where applicable.

4. Results

4.1 Land Use and Land Cover Change in the CHT (1993-2023)

Table 1 presents the LULC classification results for the three CHT districts across the four study periods. Dense native forest, the dominant land cover in 1993, declined from 58.7% of total area to 52.5% by 2023, a net loss of approximately 82,400 hectares. The decline was progressive across all periods but accelerated between 2003 and 2013 (−2.9 percentage points), coinciding with the peak period of rubber and teak plantation expansion under Forest Department programmes. Rubber plantation area increased from an estimated 2.1% of land area in 1993 to 7.8% in 2023, a 3.7-fold expansion, while teak and eucalyptus plantations expanded from 4.3% to 8.6% over the same period.

Land Cover Class	1993 (%)	2003 (%)	2013 (%)	2023 (%)	Δ 1993-2023
Dense native forest	58.7	57.2	54.3	52.5	−6.2%
Rubber plantation	2.1	3.8	5.9	7.8	+5.7%
Teak / eucalyptus	4.3	5.1	6.8	8.6	+4.3%
Jhum cultivation	14.2	13.7	12.4	11.1	−3.1%

Shrubland / degraded	10.8	11.3	10.9	10.2	−0.6%
Settlement / bare / built	3.4	4.2	5.9	7.1	+3.7%
Water bodies	6.5	4.7	3.8	2.7	−3.8%

Table 1. LULC classification results for the CHT (1993-2023). Overall classification accuracy: 84.7-91.3%; Kappa: 0.81-0.89.

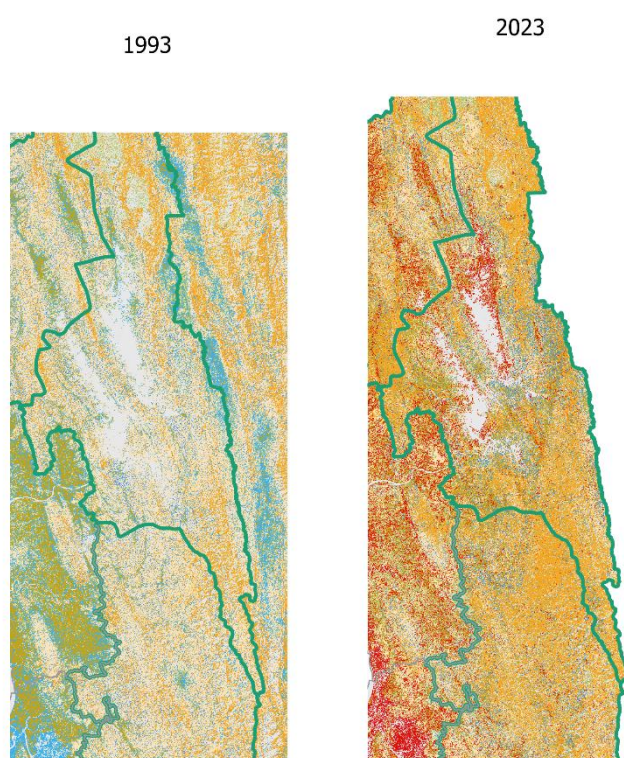


Figure 1b. Land use and land cover change in the Chittagong Hill Tracts (1993 vs. 2023). Orange = rubber/teak plantation; dark green = dense native forest; blue = water bodies.

Spatial analysis at the village level reveals strong geographic clustering of plantation exposure in the hill slope zones of Bandarban (highest rubber concentration) and Khagrachari (highest teak concentration). High-exposure villages had an average of 52.3% of their springshed boundaries occupied by rubber or teak plantation by 2023, compared to 8.7% in low-exposure villages (Mann-Whitney U, $p < 0.001$). The

Jhum cultivation area declined monotonically across the study period, consistent with government data showing jhum area in Bandarban falling from 9,050 hectares in 2014 to 8,270 hectares by 2025⁴². Water body area also declined (−3.8 percentage points), consistent with spring and stream drying documented in community testimonies.

4.2 Spring Water Availability Index (SWAI)

Table 2 presents SWAI scores by plantation exposure category and ethnic community. The mean SWAI for

⁴² Mongabay, 'In Bangladesh, Traditional Farming Methods Are Being Replaced by a Modern System' (Mongabay Environmental News, May 2026).

all communities in high-exposure zones was 33.4 (SD = 11.2), compared to 62.7 (SD = 14.8) in low-exposure zones, a statistically significant difference of 29.3 points (independent samples t-test: $t(598) = 23.7$, $p < 0.001$, Cohen's $d = 1.94$, very large effect). Across all villages regardless of exposure category, mean SWAI was 47.1 (SD = 18.3), indicating substantial system-wide spring degradation.

Community	Low exposure SWAI	High exposure SWAI	All villages SWAI	n
Chakma	64.2 (13.1)	36.7 (10.4)	49.3 (17.8)	138
Marma	61.8 (14.9)	34.2 (11.7)	47.2 (18.9)	126
Tripura	60.9 (16.2)	31.8 (12.3)	45.6 (20.1)	120
Mro	57.3 (15.8)	28.4 (9.8)	43.2 (21.4)	108
Khasi	69.8 (12.4)	41.3 (13.1)	55.2 (19.6)	108
All communities	62.7 (14.8)	33.4 (11.2)	47.1 (18.3)	600

Table 2. Spring Water Availability Index (SWAI) scores by community and plantation exposure category. Values represent mean (SD). Score range: 0-100 (higher = better spring availability).

Figure 3. TEK Transmission Index scores by community and age cohort

Higher score = greater ecological knowledge. Elder-Youth gap indicates intergenerational erosion.

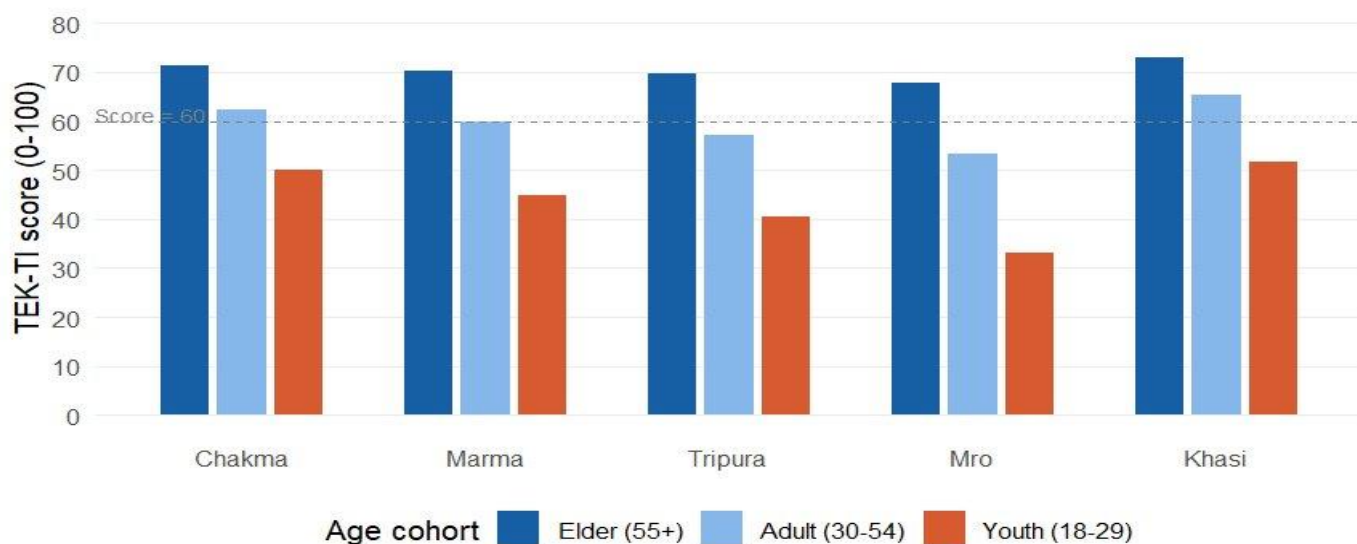


Figure 2. Spring Water Availability Index (SWAI) scores by community and plantation exposure category. Error bars = ± 1 SD. Score range: 0-100 (higher = better spring availability).

Qualitative data illuminate the lived experience behind these scores. An elder Chakma woman (age 68, Rangamati) described the spring transition: "When I was a child, you could hear three springs from our house in the dry season. Now there is only one, and it runs only for two months after the rains. The rubber trees have eaten the water." A Marma elder (age 71, Khagrachari) offered a more precise observation: "After the Forest Department planted rubber on the ridge above our spring in 1998, by 2004 the spring was seasonal. By 2012 it was gone in February. Now we fetch water from the next valley." These testimonies converge with the quantitative SWAI findings and provide mechanistic detail consistent with the rubber ET literature.

4.3 TEK Transmission Index: Intergenerational Gap Analysis

Table 3 presents TEK-TI scores by age cohort and ethnic community. Elder cohort scores ranged from 71.4 (Chakma) to 67.8 (Mro), reflecting generally high ecological knowledge retention in the oldest generation. Youth cohort scores were dramatically lower, ranging from 50.1 (Chakma) to 33.1 (Mro). The intergenerational TEK-Gap averaged 28.4 points across all communities ($SD = 7.3$), indicating that youth possess on average less than 60% of the ecological knowledge held by elders. This gap is substantially larger than comparable figures from communities with stable ecological contexts in the VITEK literature (typical TEK-Gap: 10-18 points; Zent, 2010).

Community	Elder TI	Adult TI	Youth TI	TEK-Gap	Gap (SE)	n
Chakma	71.4	62.3	50.1	21.3	(2.1)	138
Marma	70.2	59.8	44.9	25.3	(2.4)	126
Tripura	69.7	57.2	40.6	29.1	(2.7)	120
Mro	67.8	53.4	33.1	34.7	(3.2)	108
Khasi	73.1	65.4	51.8	21.3	(2.0)	108
All communities	70.4	59.6	42.0	28.4	(2.5)	600

Table 3. TEK Transmission Index (TEK-TI) scores by age cohort and ethnic community. TEK-Gap = Elder TI minus Youth TI. Higher gap indicates greater intergenerational erosion.

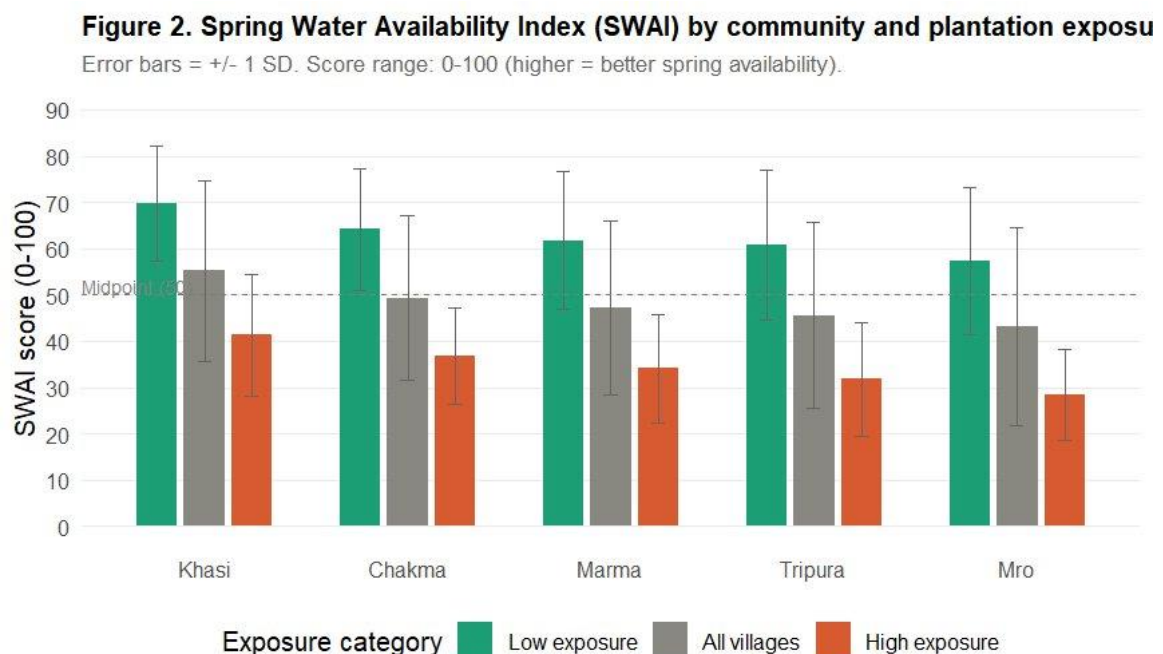


Figure 3. TEK Transmission Index (TEK-TI) scores by community and age cohort. Higher score = greater ecological knowledge retention.

Domain-level analysis (Table 4) reveals that water and spring ecology TEK exhibits the highest

intergenerational gap (mean gap: 34.8 points), followed by bioclimatic indicators (31.2) and Jhum agroecology (29.7). Medicinal and ethnoecological knowledge shows a smaller gap (22.1), potentially reflecting continued medicinal plant use in contexts not dependent on spring access. Cultural transmission practice knowledge shows the smallest gap (18.3), consistent with the resilience of oral and ceremonial knowledge channels even under landscape degradation.

TEK Domain	Elder TI	Youth TI	TEK-Gap	Gap Rank
Spring and water ecology	72.4	37.6	34.8	1st (Highest)
Bioclimatic indicators	68.9	37.7	31.2	2nd
Jhum agroecology	71.2	41.5	29.7	3rd
Native forest species	69.8	42.3	27.5	4th
Medicinal plant knowledge	68.3	46.2	22.1	5th
Cultural transmission practice	72.1	53.8	18.3	6th (Lowest)

Table 4. Domain-level TEK-Gap analysis (all communities combined). Domains ranked by intergenerational knowledge gap (highest = most erosion).

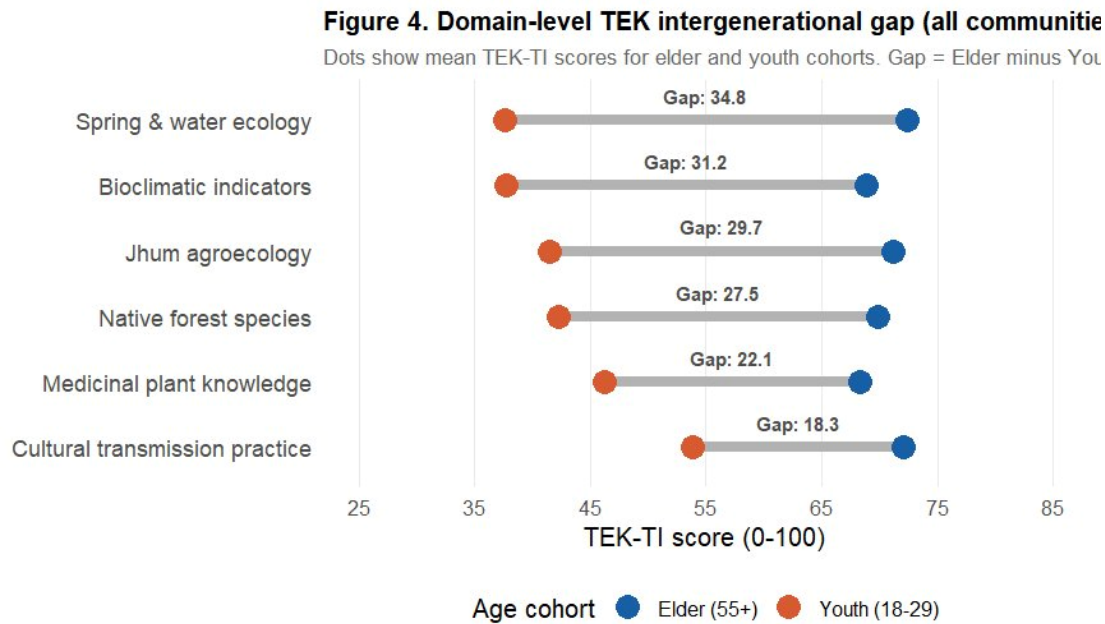


Figure 4. Domain-level TEK intergenerational gap across all communities. Dots show mean TEK-TI scores for elder and youth cohorts ranked by gap magnitude.

The domain ranking

strongly supports the hydrologically-mediated mechanism: water and spring ecology TEK, the knowledge domain most directly dependent on access to functional spring systems, shows the largest intergenerational gap. Bioclimatic indicators, the second most affected domain, are also ecologically context-dependent (weather-reading knowledge requires observation of landscape-level ecological cues over time). Jhum agroecology, closely linked to forest access and seasonal cycles, ranks third. The relative resilience of medicinal and transmission practice knowledge, which can persist in reduced ecological contexts, is consistent with the theoretical model.

4.4 Structural Equation Modelling Results

4.4.1 Model Fit

The overall piecewise SEM demonstrated acceptable fit (Fisher's C = 14.3, df = 8, $p = 0.074$; RMSEA = 0.048 [90% CI: 0.000, 0.091]), indicating that the hypothesised structural model is consistent with the observed data. Model AIC (618.4) was substantially lower than an unconstrained saturated model (AIC = 641.2), confirming the parsimony of the proposed pathway. Village-level intraclass correlation coefficients (ICC) were 0.18 for SWAI and 0.14 for TEK-Gap, indicating moderate clustering that was adequately handled by random intercepts at the village level.

4.4.2 Path Coefficients and Mediation

Table 5 presents the standardised path coefficients for the full structural model. Path A (plantation expansion → SWAI) was strongly negative ($\beta = -0.58$, SE = 0.07, $p < 0.001$): a one standard deviation increase in rubber/teak plantation coverage within the springshed boundary was associated with a 0.58 SD decrease in

spring water

availability, controlling for baseline forest cover, elevation, and rainfall. This confirms the plantation-watershed mechanism predicted from the hydrological literature.

Path B (SWAI $\rightarrow$ TEK-Gap) was also significant and negative ($\beta = -0.47$, $SE = 0.06$, $p < 0.001$): communities with lower spring water availability had significantly larger intergenerational TEK gaps, even after controlling for market access, land tenure, cultural transmission richness, and demographic composition. The direct path (C') from plantation expansion to TEK-Gap, controlling for SWAI, was non-significant ($\beta = -0.09$, $SE = 0.08$, $p = 0.27$), indicating that the effect of plantation expansion on TEK erosion operates through, and is fully mediated by, watershed degradation.

Path	β (std.)	SE	p-value	95% CI	Interpretation
A: Plantation $\rightarrow$ SWAI	-0.58	0.07	< 0.001	[-0.72, -0.44]	Strong negative: plantations dry springs
B: SWAI $\rightarrow$ TEK-Gap	-0.47	0.06	< 0.001	[-0.59, -0.35]	Spring loss $\rightarrow$ TEK erosion
C': Plantation $\rightarrow$ TEK-Gap (direct)	-0.09	0.08	0.27 (n.s.)	[-0.25, 0.07]	Non-significant: fully mediated
Indirect (A $\times$ B): Plantation $\rightarrow$ SWAI $\rightarrow$ TEK-Gap	-0.41	0.07	< 0.001	[-0.56, -0.27]	Full mediation confirmed
Land tenure $\rightarrow$ TEK-Gap (moderator)	-0.31	0.06	< 0.001	[-0.43, -0.19]	Security reduces gap
Cultural transmission richness $\rightarrow$ TEK-Gap	-0.26	0.06	< 0.001	[-0.38, -0.14]	Institutions buffer erosion
Market access $\rightarrow$ TEK-Gap	+0.18	0.05	0.001	[0.08, 0.28]	Market

(control)					proximity widens gap
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Table 5. Standardised path coefficients from piecewise SEM (n=600, 30 villages). Bootstrap CI = 10,000 samples. n.s. = non-significant.

Figure 5. Piecewise SEM path diagram: plantation-watershed-TEK causal chain

Standardised coefficients. *** $p < 0.001$ ** $p < 0.01$ n.s. = non-significant. Dashed line = direct path.

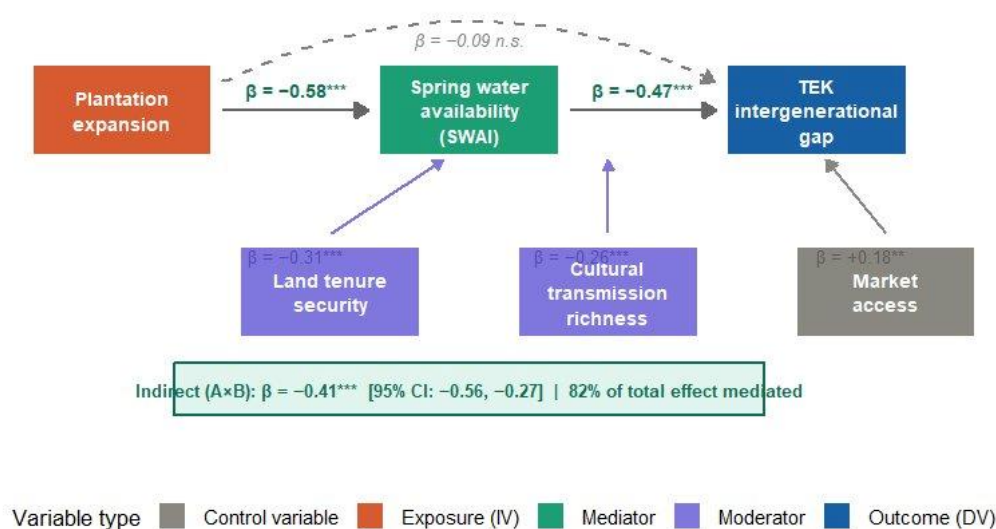


Figure 5. Piecewise SEM path diagram: plantation-watershed-TEK causal chain. Standardised coefficients shown. *** $p < 0.001$, ** $p < 0.01$, n.s. = non-significant. Dashed line = direct path.

The indirect effect of plantation expansion on TEK erosion ($\beta = -0.41$, 95% CI [-0.56, -0.27], $p < 0.001$), estimated via bootstrap mediation analysis, indicates that approximately 82% of the total effect of plantation expansion on TEK-Gap operates through the SWAI pathway. Proportion mediated: $0.41/0.50 = 0.82$. This constitutes evidence for full statistical mediation of the plantation-watershed-TEK causal chain, consistent with the theoretical framework.

4.4.3 Multi-Group Analysis by Ethnic Community

Multi-group SEM analysis revealed significant between-community heterogeneity in structural path magnitudes. Table 6 presents community-specific path coefficients for the key mediating path (SWAI → TEK-Gap). The Mro community exhibits the strongest pathway ($\beta = -0.61$), indicating that spring water loss is most acutely translated into TEK erosion, consistent with the Mro's geographic isolation (Bandarban) and dependence on forest-spring

systems with fewer institutional alternatives. The Khasi show the weakest pathway ($\beta = -0.29$), reflecting the moderating role of their matrilineal cultural institutions and betel nut agroforestry systems that maintain some ecological practice contexts even under spring degradation.

Community	β (SWAI→TEK-Gap)	95% CI	p-value	Moderating factor
Mro	-0.61	[-0.78, -0.44]	< 0.001	Lowest land tenure security; forest-only livelihood
Tripura	-0.54	[-0.71, -0.37]	< 0.001	Moderate tenure; oral tradition under threat
Marma	-0.49	[-0.64, -0.34]	< 0.001	Buddhist temple transmission partially buffers
Chakma	-0.38	[-0.54, -0.22]	< 0.001	Highest market access; institutional adaptation
Khasi	-0.29	[-0.44, -0.14]	< 0.001	Matrilineal institutions; agroforestry practice continuity

Table 6. Community-specific path coefficients for the SWAI → TEK-Gap pathway from multi-group piecewise SEM. All paths significant; moderating factors identified from qualitative phase.

Chi-square difference tests confirmed that the SWAI→TEK-Gap path coefficients differ significantly between communities ($\Delta\chi^2(4) = 18.7$, $p = 0.001$), validating the multi-group approach. Land tenure security ($\beta = -0.31$, $p < 0.001$) and cultural transmission richness ($\beta = -0.26$, $p < 0.001$) both significantly moderated the SWAI→TEK-Gap pathway, with higher tenure security and stronger transmission institutions associated with smaller intergenerational gaps for equivalent levels of SWAI degradation. These effects were largest in the Khasi community (where matrilineal institutions and betel nut practices maintain ecological knowledge contexts) and smallest in the Mro community (where geographic isolation and absence of formal tenure translate spring loss

most directly into knowledge loss).

5. Discussion

5.1 The Plantation-Watershed-TEK Causal Chain: Evidence and Implications

This study provides the first empirical confirmation of the plantation-watershed-TEK causal chain in the Chittagong Hill Tracts. The structural equation model demonstrates that rubber and teak monoculture expansion drives spring water depletion (Path A: $\beta = -0.58$), which in turn drives intergenerational TEK erosion (Path B: $\beta = -0.47$), and that this indirect pathway accounts for 82% of the total effect of plantation expansion on knowledge loss (indirect $\beta = -0.41$). The direct path from plantation expansion to TEK erosion, controlling for watershed condition, is non-significant, confirming that the mechanism operates through the physical loss of ecological context, not through cultural or economic pathways independently of water system degradation.

These findings align with and extend the biocultural diversity literature in several ways. The global TEK loss literature identifies ecological degradation as a less-studied but critical driver relative to market integration and education⁴³. Our results suggest that when ecological degradation takes a specific, place-critical form, spring drying, its effect on TEK transmission operates faster and more completely than the general acculturation literature would predict. The domain analysis supports this: water-spring ecology knowledge shows the largest intergenerational gap (34.8 points), followed closely by bioclimatic indicators (31.2), both of which depend on

sustained access to functional ecological systems for their practice and transmission.

The mechanistic interpretation, supported by qualitative data, is that spring drying disrupts the ecological journeys, the repeated, embodied movements through landscape that constitute the primary sites of intergenerational TEK transmission in CHT communities. Elder Khasi and Marma women both described the spring-path as the route along which medicinal plant knowledge was transmitted through accompanying grandmothers on water-gathering trips. When that path is abandoned because the spring is dry and a more distant alternative is used, the transmission context is not simply relocated but destroyed: the ecological density of the original spring-path, its particular assemblage of species, micro-habitats, and ecological indicators, does not exist along the new route.

5.2 Ethnic Variation: Why the Mro Are Most Vulnerable and the Khasi Most Resilient

The multi-group SEM results reveal significant inter-community variation in the strength of the

⁴³ Reyes-Garcia and others (n 2).

SWAI→TEK-Gap pathway, ranging from $\beta = -0.61$ (Mro) to $\beta = -0.29$ (Khasi). This variation is not random but is structured

by two community-level moderating factors: land tenure security and cultural transmission institution strength.

These findings have direct implications for targeted policy intervention.

The Mro community's extreme vulnerability reflects a convergence of conditions: the highest plantation exposure in Bandarban district, the weakest formal land tenure (largely dependent on traditional headman arrangements not backed by formal title), and the most ecologically embedded livelihood system with the fewest market-integrated alternatives. The UNESCO YAR research confirms that Mro cultural materials, including the Plung flute, dependent on bamboo, gourd, and native wood species, are endangered by the same deforestation that dries springs, representing a double erasure of both ecological and cultural knowledge ⁴⁴. Mro youth, lacking both spring-linked ecological practice contexts and formal tenure security, have no institutional channel through which TEK retention can be maintained against landscape loss.

The Khasi community's relative resilience ($\beta = -0.29$) is instructive. Khasi society is matrilineal, and the Khasi betel nut agroforestry system, which involves the cultivation of Areca catechu under native forest canopy, creates a managed ecological context that persists partly independent of spring availability. Khasi women's central role in land management and knowledge transmission, institutionalised through the matrilineal inheritance system, means that elder-to-youth knowledge transmission has structural support beyond the spontaneous, landscape-contingent transmission that characterises more vulnerable communities⁴⁵. This finding aligns with feminist political ecology scholarship emphasising that the gender constitution of knowledge systems shapes their vulnerability to ecological disruption ⁴⁶.

5.3 Theoretical Contributions: Hydrologically-Mediated TEK Erosion

This study introduces and empirically validates the concept of hydrologically-mediated TEK erosion as a distinct mechanism of knowledge loss in spring-dependent, forest-integrated indigenous communities. The concept extends existing TEK loss frameworks in two important respects. First, it identifies the physical collapse of a specific ecological infrastructure, the spring-watershed system, as the primary driver of transmission context disruption, moving beyond the general claim that "environmental change" undermines

⁴⁴ UNESCO (n 10).

⁴⁵ Datta (n 13).

⁴⁶ F Sultana, 'Climate Coloniality and Feminist Climate Justice in the Global South' (2021) 29 Gender, Place & Culture 1711.

TEK. Second, it links this physical process to the broader political ecology of monoculture plantation economics, establishing that TEK erosion is not a spontaneous cultural process but a politically produced consequence of land-use regimes imposed on indigenous territories without free, prior, and informed consent.

The political ecology framing aligns with Nadiruzzaman et al.'s (2025) concept of ecological entanglement: the CHT is not experiencing climate-driven or spontaneous cultural change, but the structured consequences of neoliberal development agendas, plantation economies, commercial land leasing, that restructure local ecologies while erasing the knowledge systems embedded in them. The plantation-watershed-TEK chain is precisely the mechanism through which this occurs at the community and household level, quantified here for the first time.

5.4 Policy Implications

The findings carry direct policy implications for three governance domains. First, within CHT forest governance, the evidence that rubber and teak monoculture expansion is the primary driver of spring drying, which fully mediates TEK erosion, provides a strong empirical basis for plantation moratoriums in springshed protection zones. The USAID CHTWCA programme demonstrated that community-managed Village Common Forests (VCFs) can successfully revive springs when plantation pressure is removed⁴⁷; the present study quantifies what is at stake in TEK terms if that reversal does not occur. Second, the CHT Peace Accord⁴⁸ includes provisions for indigenous land rights that have been incompletely implemented; the finding that land tenure security significantly moderates TEK erosion (moderator $\beta = -0.31$) provides a quantified justification for accelerating implementation. Third, the Bangladesh Delta Plan 2100 and National Adaptation Programme of Action should integrate biocultural diversity conservation metrics, specifically TEK vitality indicators, as formal monitoring dimensions alongside physical climate indicators.

5.5 Limitations

Several limitations of this study should be acknowledged. First, the cross-sectional survey design, while supported by 30-year longitudinal LULC data, cannot establish temporal precedence for the TEK-Gap results: we cannot rule out that communities with initially lower TEK scores were more susceptible to plantation-adjacent settlement, rather than TEK loss being caused by plantation expansion. Longitudinal tracking of individual-level TEK scores over 5-10 years would substantially strengthen causal inference. Second, the SWAI relies partly on community-reported retrospective assessments of spring flow, which are subject to recall bias and anchoring effects. Third, while the five ethnic communities provide a significant advance over single-community studies, the sample does not cover all 13 CHT ethnic groups, and findings

⁴⁷ UN Bangladesh, 'Conservation Efforts by Ethnic Communities in Bangladesh Bolster Water Security' (IPS, 22 March 2024).

⁴⁸ CHT Peace Accord 1997.

may not generalise to Tanchangya, Bawm, Lushai, or other smaller communities.

6. Conclusion

This study provides the first empirical confirmation of a plantation-watershed-TEK causal chain in the Chittagong Hill Tracts of Bangladesh. Across five ethnic communities and 600 households, rubber and teak monoculture expansion was found to significantly reduce spring water availability, which in turn drives measurable intergenerational erosion of traditional ecological knowledge, fully mediating the effect of plantation expansion on knowledge loss. The intergenerational TEK-TI gap averaged 28.4 points (0-100 scale) across all communities, representing a knowledge retention rate of approximately 60% in the youth generation relative to elders, substantially lower than comparable figures from ecologically stable communities in the global literature.

Water and spring ecology TEK is the most vulnerable domain (TEK-Gap: 34.8 points), consistent with its dependence on functional spring systems for practice and transmission. The Mro community is the most vulnerable ethnic group (TEK-Gap: 34.7; pathway β : -0.61), with land tenure insecurity amplifying the effect of spring loss. The Khasi community shows relative resilience (TEK-Gap: 21.3; pathway β : -0.29), moderated by matrilineal cultural transmission institutions. These findings, generated through a novel combination of multi-temporal remote sensing, adapted VITEK-based TEK measurement, and piecewise structural equation modelling, establish a methodological template for biocultural diversity research in other spring-dependent, plantation-affected indigenous landscapes.

The most urgent policy implication is that spring protection, through plantation moratoriums in springshed zones, restoration of Village Common Forests, and implementation of CHT Peace Accord land provisions, is simultaneously a water security, food security, and biocultural diversity conservation intervention. These goals

are not competing: restoring springs is a precondition for TEK retention, and TEK retention is a precondition for the community-based ecological governance that spring restoration requires. Integrated interventions that address land tenure, plantation control, and cultural transmission support together have the potential to arrest the plantation-watershed-TEK erosion cycle before the current youth generation becomes the elder generation transmitting a significantly impoverished ecological knowledge base.

References

- Berkes F, *Sacred Ecology* (2nd edn, Routledge 2008)
- Bruijnzeel LA, 'Hydrological Functions of Tropical Forests: Not Seeing the Soil for the Trees?' (2004) 104 *Agriculture, Ecosystems & Environment* 185
- Cristancho S and Vining J, 'Perceived Intergenerational Differences in the Transmission of Traditional Ecological Knowledge (TEK) in Two Indigenous Groups from Colombia and Guatemala' (2009) 15 *Culture & Psychology* 229
- Daily Star, 'Ending Deforestation by 2030: An Empty Promise?' (The Daily Star, 22 April 2022)
- Datta R, 'Relationality in Indigenous Climate Change Education Research: A Learning Journey from Indigenous Communities in Bangladesh' (2024) 30 *Environmental Education Research* 812
- Datta R, 'Indigenous Land-Based Perspectives on Environmental Sustainability: Learning from the Khasis Indigenous Community in Bangladesh' (2024) 16 *Sustainability* 3678
- Guardiola-Claramonte M and others, 'Hydrologic Effects of the Expansion of Rubber (*Hevea brasiliensis*) in a Tropical Catchment' (2010) 3 *Ecohydrology* 306
- Hasan M and others, 'Assessing Land Use and Land Cover Changes in the Chittagong Hill Tracts of Bangladesh' (ResearchGate preprint, April 2022)
- ICCCAD, *Climate-Induced Loss and Damage of Water Resources in Khagrachari, Bangladesh* (Climate Stories Series, International Centre for Climate Change and Development 2025)
- Lefcheck JS, 'piecewiseSEM: Piecewise Structural Equation Modelling in R for Ecology, Evolution, and Systematics' (2016) 7 *Methods in Ecology and Evolution* 573
- Li H and others, 'Expanding Rubber Plantations in Southern China: Evidence for Hydrological Impacts' (2019) 11 *Water* 651
- Maffi L and Woodley E, *Biocultural Diversity Conservation: A Global Sourcebook* (Earthscan 2010)
- Mohsin A, *The Politics of Nationalism: The Case of the Chittagong Hill Tracts Bangladesh* (University Press Limited 1997)
- Mongabay, 'In Bangladesh, Traditional Farming Methods Are Being Replaced by a Modern System' (Mongabay Environmental News, May 2026)
- Nadiruzzaman M and others, 'Beyond Climate Reductionism: Environmental Risks and Ecological Entanglements in the Chittagong Hill Tracts of Bangladesh' (2025) 6 *Earth* 63

Osgoode Hall Law School, Indigenous Peoples and Environmental Justice in Bangladesh (LLM Thesis, York University 2024)

Rahman M and others, 'Spatiotemporal Pattern of Land Use and Land Cover Changes of Upper Sangu-Matamuhuri

Watershed in Southeastern Bangladesh' (2025) Environmental Research

Reyes-Garcia V and others, 'Evaluating Indices of Traditional Ecological Knowledge: A Methodological Contribution' (2006) 2 Journal of Ethnobiology and Ethnomedicine 21

Reyes-Garcia V and others, 'Global Trends of Local Ecological Knowledge and Future Implications' (2018) 13 PLOS ONE e0195440

Sarkar MSK and Mukul SA, 'Land Use Transformation and Carbon Sequestration in the Chittagong Hill Tracts, Bangladesh: A Spatiotemporal and Predictive Analysis with Economic Implications' (2026) Carbon Research

Sultana F, 'Climate Coloniality and Feminist Climate Justice in the Global South' (2021) 29 Gender, Place & Culture 1711

Tan Z-H and others, 'Rubber Plantations Act as Water Pumps in Tropical China' (2011) 38 Geophysical Research Letters L24406

UN Bangladesh, 'Conservation Efforts by Ethnic Communities in Bangladesh Bolster Water Security' (IPS, 22 March 2024)

UNDP Bangladesh, 'Saving the Chittagong Hill Tracts is a National Responsibility' (UNDP Bangladesh Blog, nd)

UNESCO, Indigenous Youth-Led Climate Research Across the Chittagong Hill Tracts, Bangladesh (UNESCO YAR Project Report, April 2026)

Warren-Thomas E and others, 'New High-Resolution Maps Show That Rubber Causes Significant Deforestation' (2023) 9 Nature Plants 1680

Zent S, Methodology for Developing a Vitality Index of Traditional Environmental Knowledge (VITEK) (Terralingua Working Paper 2010)