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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 harbours 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 (piecewise SEM) 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 averaged 28.4 points across communities, with the Mro community exhibiting the highest gap. 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 diversity (Maffi & Woodley, 2010). 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 cases (Reyes-García et al., 2018). 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 km^2 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 others (Mohsin, 1997). 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 2000s (Daily Star, 2022). Concurrently, military-linked settlement programmes 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 period (Sarkar & Mukul, 2026). 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 year (Rahman et al., 2025).

The hydrological consequences of plantation expansion are well 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 behaviour (Guardiola-Claramonte et al., 2010). A drying of streamflow was observed downstream of the rubber plantation in the dry season, while the stream coming from the tropical forest remained perennial (Li et al., 2019). 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 failure (ICCCAD, 2025).

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 disappeared (UNESCO, 2026). Nadiruzzaman et al. (2025) 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.

Accordingly, this study aims to examine whether plantation-induced watershed degradation mediates the relationship between landscape transformation and intergenerational TEK erosion among Indigenous communities in the Chittagong Hill Tracts of Bangladesh

1.1 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 practice (Berkes, 2008). 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 relations (Datta, 2024a). 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 points (Zent, 2010). 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 change (Zent, 2010). 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 erosion (Reyes-García et al., 2018). Cristancho and Vining (2009) 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 abstracted classroom knowledge is precisely the dynamic hypothesised in this study because of spring drying and forest loss in CHT.

1.2 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 inputs (Guardiola-Claramonte et al., 2010). 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.

1.3 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 organized 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 retention (UNESCO, 2026). 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 accelerat[ing] cultural erosion" (UNESCO, 2026).

The relational learning framework developed by Datta (2024a) 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 become unavailable or degraded.

1.4 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 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 environment changes specifically, the collapse of spring-fed water systems serves 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

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted across all three districts of the Chittagong Hill Tracts: Rangamati (6,116 km^2), Khagrachari (2,699 km^2), and Bandarban (4,479 km^2). 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) (UNDP Bangladesh, n.d.). 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 springshed boundary), ten in moderate-exposure zones (20–40%), and ten in low-exposure zones (<20%).

2.2 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).

Figure 1a: Study area: Chittagong Hill Tracts, Bangladesh showing the three study districts (Rangamati, Khagrachhari, Bandarban) and 30 study villages stratified by plantation exposure zone.

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.

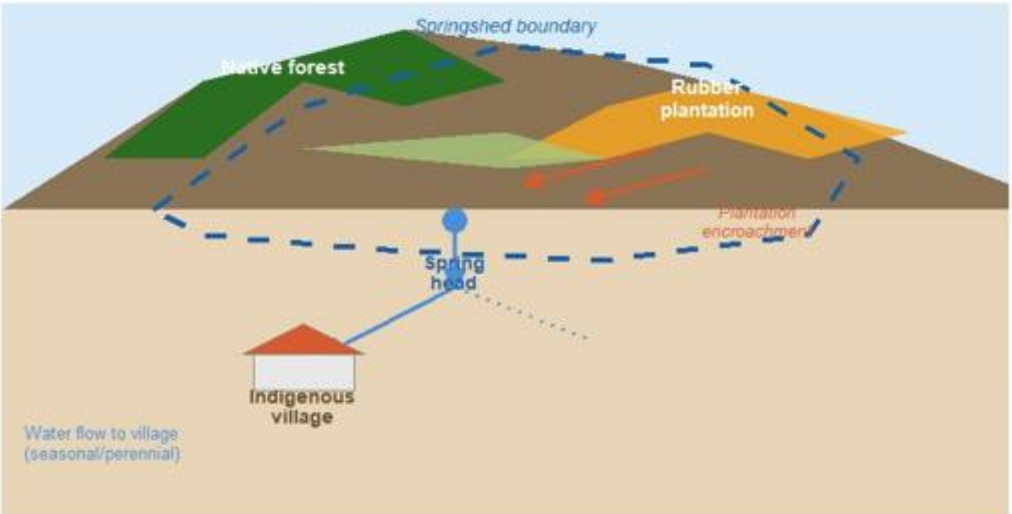

Figure 1c. Conceptual springshed delineation showing the plantation-spring-village linkage. Dashed line = springshed boundary; red arrows = plantation encroachment direction.

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).

2.3 Phase 2: Household Survey and TEK-TI Instrument

2.3.1 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.

2.3.2 TEK Transmission Index

The TEK Transmission Index (TEK-TI) instrument was developed through adaptation of the VITEK methodology (Zent, 2010) combined with the Cultural Significance Index approach used in Amazonian ethnobiology (Reyes-García et al., 2006). 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) 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.

2.4 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 approach (Tavory & Timmermans, 2014), with deductive codes derived from the SEM framework and inductive codes emerging from community narratives.

2.5 Structural Equation Modelling

Piecewise structural equation modelling (piecewiseSEM) was implemented in R (v.4.3.1) using the piecewiseSEM package (Lefcheck, 2016), 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 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.

3. Results

3.1 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.

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

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%

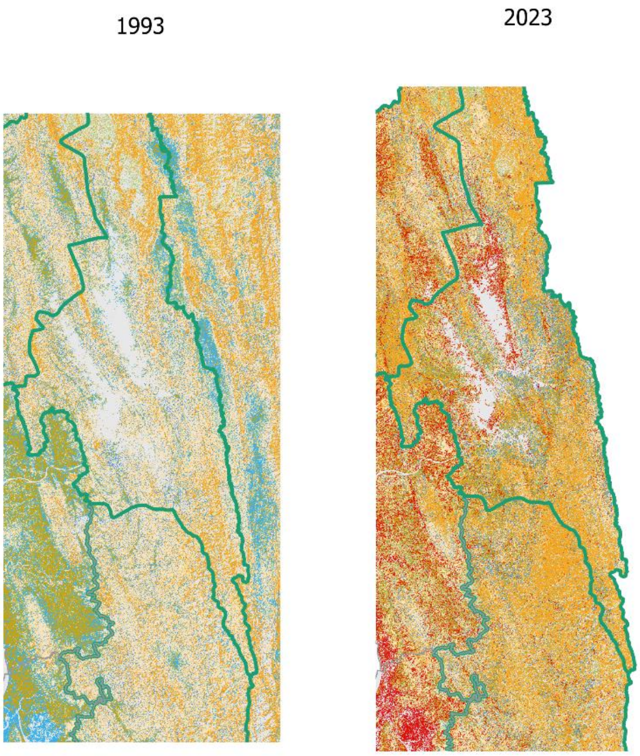

Figure 1b. Land use and land cover change in the Chittagong Hill Tracts (1993 vs. 2023). Orange = rubber/teak plantation; dark green = dense native forest; blue = water bodies.

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 2025 (Mongabay, 2026). Waterbody area also declined (−3.8 percentage points), consistent with spring and stream drying documented in community testimonies.

3.2 Spring Water Availability Index (SWAI)

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

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).

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

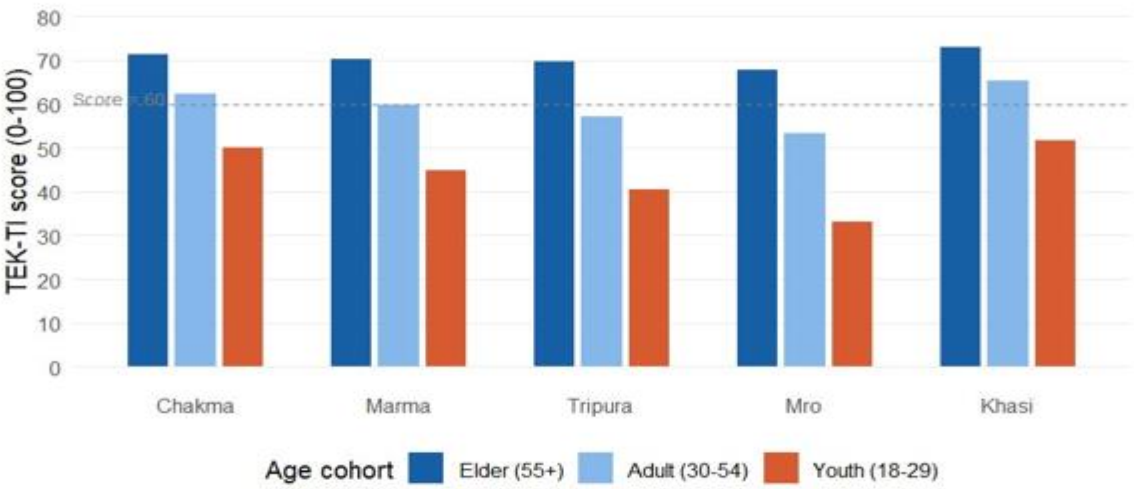

Figure 2. Spring Water Availability Index (SWAI) scores by community and plantation exposure category. Error bars = ±1 SD. Score range: 0-100 (higher = better spring availability).

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 rain. 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.

3.3 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).

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

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

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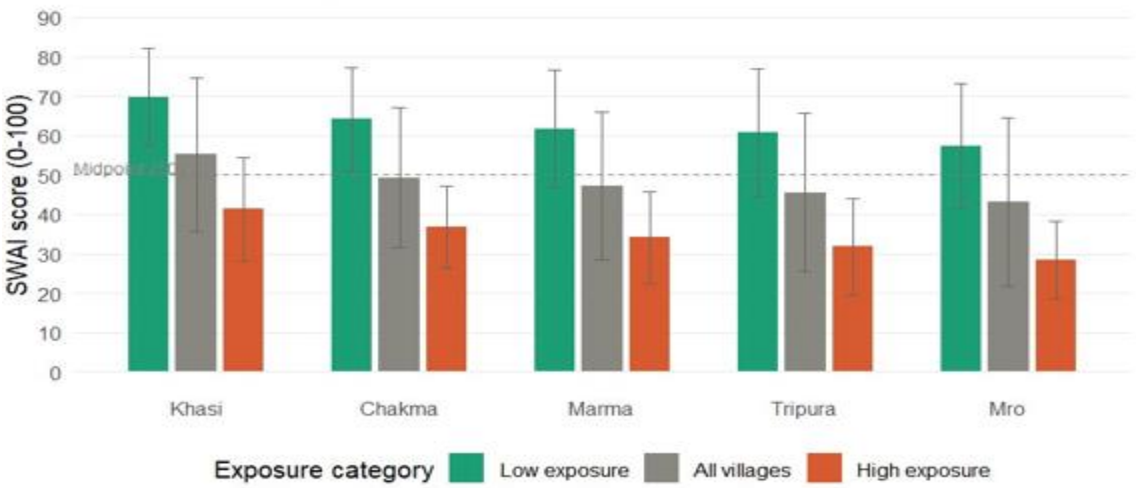

Figure 3. TEK Transmission Index (TEK-TI) scores by community and age cohort. Higher score = greater ecological knowledge retention.

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

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.

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

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)

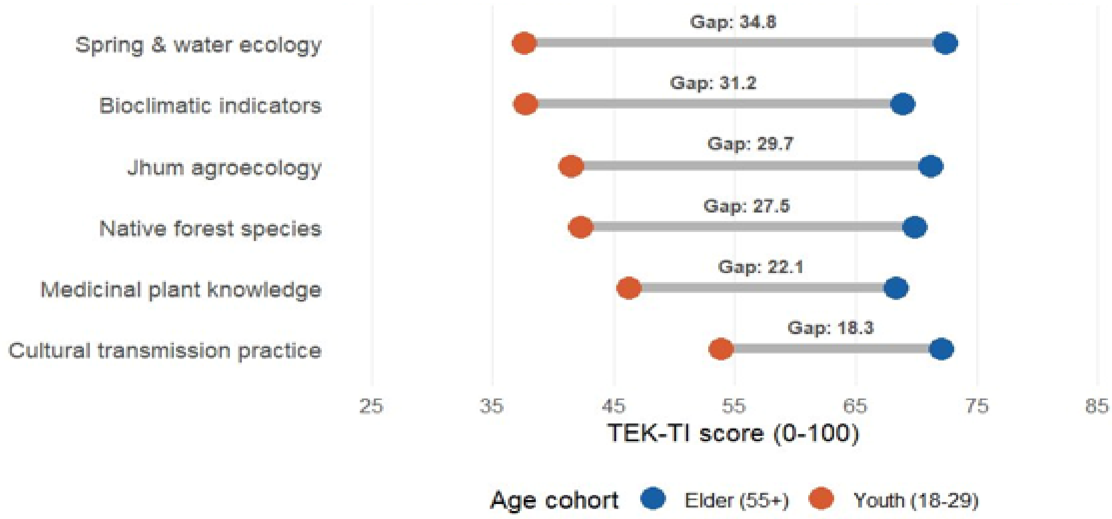

Figure 4. Domain-level TEK intergenerational gap across all communities. Dots show mean TEK-TI scores for elder and youth cohorts ranked by gap magnitude.

3.4 Structural Equation Modelling Results

3.4.1 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.

3.4.2 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 → 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.

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

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

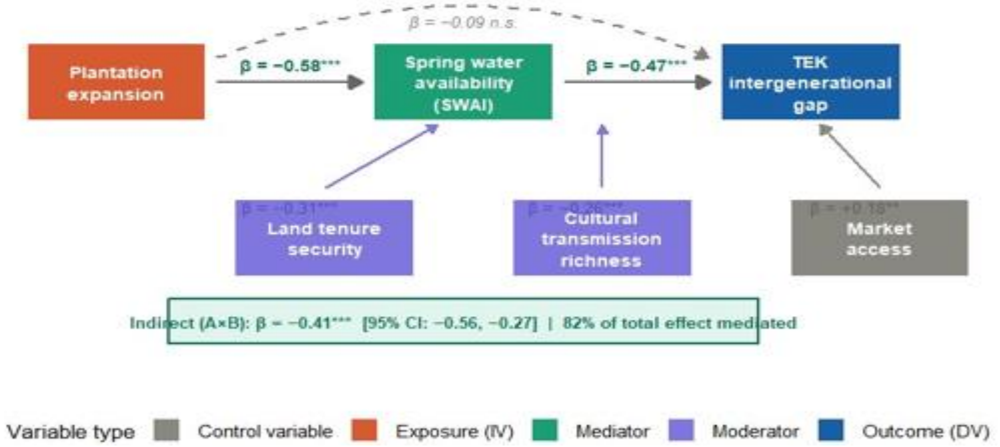

Figure 5. Piecewise SEM path diagram: plantation-watershed-TEK causal chain. Standardised coefficients shown. ***p<0.001, **p<0.01, n.s. = non-significant. Dashed line = direct path.

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.

3.4.3 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.

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.

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

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).

4. DISCUSSION

4.1 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 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 education (Reyes-García et al., 2018). 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.

4.2 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 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 (UNESCO, 2026). 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 communities (Datta, 2024b). This finding aligns with feminist political ecology scholarship emphasising that the gender constitution of knowledge systems shapes their vulnerability to ecological disruption (Sultana, 2021).

4.3 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 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.

4.4 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 removed (UN Bangladesh, 2024); the present study quantifies what is at stake in TEK terms if that reversal does not occur. Second, the CHT Peace Accord (1997) 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.

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

5. 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.

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