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Mapping Hill and Mountain Ecosystem in India: A Review and Framework for Ecological Production Units (EPUs)

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ABSTRACT

Mountain and hill ecosystems (the Himalaya-Northwest hills and Northeast hills, Aravalli, Western Ghats, and Eastern Ghats) in India provide critical ecosystem services, including biodiversity conservation, water regulation, and livelihood support, yet their spatial heterogeneity is poorly captured by existing classification frameworks. This paper presents a narrative synthesis of global and Indian approaches to mapping mountain ecosystems and evaluates their suitability for land-use planning in complex upland regions. We review major frameworks, including biogeographic zones, agro-ecological regions, watershed divisions, WWF ecoregions, and global mountain classifications, highlighting their strengths and limitations in representing ecological and production variability. A key gap identified is the absence of an integrated, operational unit that combines ecological, climatic, and socio-economic dimensions for planning purposes. To address this, we propose a conceptual multi-criteria GIS-based framework for delineating Ecological Production Units (EPUs) in Indian hill regions. The framework integrates topography, climate, soils, land cover, and human factors to define homogeneous units of ecological productivity and management relevance. The study demonstrates that EPUs can serve as a bridge between ecological classification and decision-making, with applications in watershed management, agroforestry, conservation planning, and climate adaptation. However, implementation is constrained by data gaps, scale mismatches, and institutional fragmentation. The paper contributes a structured synthesis of classification systems and provides a conceptual pathway toward operationalizing spatially explicit, ecosystem-based planning in India's hill and mountain regions.

1 | INTRODUCTION

Mountain and hill regions are globally recognized as ecological hotspots that sustain biodiversity and provide critical ecosystem services. Approximately 27% of Earth's land surface is mountainous, and these areas contain 25 of the world's 34 biodiversity hotspots (Kapos *et al*., 2000). They support water resources by intercepting monsoon rainfall and have high carbon storage and agro-diversity. In India, major mountain and hill systems, such as the Himalaya in the north, the Western and Eastern Ghats in the south, and the northeastern hill chains, are rich in endemic species. The Western Ghats, a UNESCO World Heritage site, are home to at least 325 globally threatened species and are one of only eight "hottest" biodiversity hotspots (Myers *et al*., 2000). Hill ecosystems also support millions of rural livelihoods through terrace agriculture, forestry, and pasture. The Indian Himalayas are especially significant. They encompass the highest and youngest mountain systems globally and represent a critical agroecosystem that supports approximately 75% of India's workforce. These regions are essential for both livelihood security and environmental stability, significantly influencing the sub-continent's climate by regulating monsoon patterns and preventing cold continental air from moving southward. The Himalayan region also provides approximately 1,204 km³ of perennial water flow annually to the Indo-Gangetic plains through snowmelt and glacial systems (Singh *et al*., 2011).

However, these landscapes are highly heterogeneous, with steep slopes, varied soils, and microclimates, and are increasingly vulnerable to deforestation, erosion, and climate change. Integrated planning (e.g., watershed management, agroforestry, integrated farming system) requires mapping upland ecosystems into homogeneous units that reflect natural productivity patterns and constraints. In this context, the concept of Ecological Production Units (EPUs) has gained attention. Adapted from marine ecology, EPUs are spatial units defined by consistent environmental and biological attributes, essentially homogeneous in ecological productivity. For terrestrial systems, EPUs can be seen as contiguous areas of land with similar topography, climate, soils, and land use, yielding uniform potentials for agriculture, forestry, and conservation.

This review synthesizes how hill and mountain ecosystems are characterized and mapped globally and within India, emphasizing zonation frameworks and data sources. We examine Indian mapping efforts such as NRSC land-use/cover maps, NBSS&LUP agroecological zones, biogeographic zones, and watershed hierarchies, along with international schemes like WWF ecoregions, FAO agroecological zones, EPA ecoregions, Kapos mountain classes, and GMBA inventory. A practical multi-criteria EPU mapping framework is proposed for India's hill regions, including discussions on applications to watershed planning, agroforestry, conservation, and climate resilience. Despite multiple classification frameworks, existing approaches remain fragmented and sector-specific. There is a lack of spatial units that simultaneously capture ecological processes, production potential, and management relevance. This paper addresses the following questions: (i) How are hill and mountain ecosystems currently classified? (ii) What are the strengths and limitations of existing frameworks? (iii) How can EPUs provide an integrative operational framework? The study aims to synthesise classification approaches and propose a conceptual EPU framework tailored to Indian conditions.

2 | METHODS

This review conducted a systematic literature survey of peer-reviewed articles, technical reports, and agency documents on the classification of hill and mountain ecosystems in India and globally. We searched databases (Web of Science, Google Scholar) and agency websites using keywords such as "mountain ecosystem India," "hill agroecological mapping," "ecoregion classification India," "watershed zonation," and "ecological production units." Government and institutional sources (ISRO/NRSC, ICAR–NBSSLUP, UNESCO, FAO, etc.) were included. We analysed definitions (e.g., FAO/UNEP mountain classes), data sources (DEM, climate, soil maps, LULC), and classification schemes. Comparative international examples (WWF ecoregions, NOAA EPUs, GMBA inventory) were reviewed to identify relevant criteria. Based on the synthesis, we drafted a multi-criteria framework tailored to Indian hill zones, outlining data inputs, processing steps, major gaps, and policy linkage issues.

2.1 | Definitions and Characteristics

There is no single universal definition of "hills" versus "mountains." Mountain areas are most commonly defined by elevation and slope criteria. FAO and UNEP's global definition (used in SDG 15.4.2) classifies mountains into seven altitude–slope "Kapos classes" (Kapos *et al*., 2000): for example, terrain ≥4,500 m (Class 1), ≥3,500 m (Class 2), ≥2,500 m (Class 3), or lower altitudes with minimum slopes (e.g., ≥1,000 m with slope ≥5°, Class 5). By these rules, many of India's foothills qualify as mountain areas if they have steep relief. In some legal contexts, arbitrary criteria have also been applied; for example, the Indian Supreme Court recently defined "Aravalli Hill ranges" as any landform ≥100 m high with ≥500 m gap between hills. In ecosystem terms, hill and mountain ecosystems are typically rugged terrain with altitude-driven climate gradients, featuring montane forests, grasslands, and alpine zones that contrast with adjacent lowland plains (Fig. 1).

HIGHLIGHTS

- The complex hill ecosystems require integration of multiple classification systems (biogeographic, agro-ecological, hydrological, and global) as each capture only one dimension of a complex landscape.
- A GIS-based, multi-criteria Ecological Production Unit framework integrating topography, climate, soils, and land cover can enable more targeted conservation, agroforestry, and climate adaptation than coarse administrative zones.
- Supporting 75% of India's agricultural workforce and supplying 1,204 km³ of annual water flow, the Himalayas face accelerating threats from population pressure, mining, and glacial retreat.
- Outdated soil maps, infrequent land-cover surveys, and inter-agency silos hinder EPU adoption; progress requires updated geospatial data, participatory mapping, and stronger policy mandates.

FIGURE 1 Hill and Mountain Ecosystems of India

2.2 | Ecological Production Units (EPUs)

A central goal of mapping is to partition the landscape into homogeneous ecological units — areas relatively uniform in abiotic conditions and ecological response. In landscape ecology, analogous terms like *ecotope* or *habitat unit* have been used (Forman & Godron, 1986; Turner *et al*., 2001): they are spatially explicit, homogeneous landscape units useful for stratification. The EPU concept stresses functional productivity: an EPU should represent a zone with consistent potential for biomass production or ecosystem services given its environment. NOAA's EPUs on the US continental shelf are defined using "physiographic, oceanographic, and biological variables." Similarly, terrestrial EPUs would integrate topography, climate, soils, vegetation, and land use. By mapping EPUs in hilly regions, planners can identify areas sharing similar constraints (e.g., erosion risk) and potentials (e.g., suitable cropping systems).

2.3 | Scale and Hierarchy

Homogeneous units can be defined at multiple scales, from macro ecoregions to micro-watersheds. For instance, Rodgers and Panwar's (1988) biogeographic zones partition India into 10 major zones (e.g., Trans-Himalaya, Himalaya, Western Ghats), each containing several provinces. Within these, agroecological subregions (NBSS&LUP, 1999) further refine areas based on soil and climate. Watershed hierarchies form another nested scheme. An effective EPU mapping thus employs a hierarchical approach — broad zones divided into finer units — reflecting ecological theory that processes (climate patterns, species communities) operate differently at different scales.

3 | GLOBAL AND INDIAN CLASSIFICATION FRAMEWORKS

3.1 | Global Frameworks

3.1.1 | Kapos Mountain Classes (UNEP-WCMC/FAO)

Developed by UNEP's World Conservation Monitoring Centre in 2000, the Kapos classification assigns 6–7 global mountain classes based on elevation, slope, and local relief (Kapos *et al*., 2000). For example, Class 1 is ≥4,500 m, Class 4 is 1,500–2,499 m with slope >3.5°, and Class 6 is 300–999 m with local elevation >300 m. Using global DEMs such as GMTED2010 or GTOPO30, it identifies about 24–26% of the land as mountainous. It aims to create a simple, reproducible global mountain map widely used for SDG 15.4 monitoring, relying solely on topography (Table 1). However, fixed thresholds can misclassify terrain, and they overlook climate and ecological zones. While useful as a baseline, it needs additional biological or climatic data for biodiversity or local planning purposes (Snethlage *et al*., 2022).

3.1.2 | WWF Terrestrail Ecoregions

Olson *et al.* (2001) define about 867 terrestrial ecoregions worldwide, grouped into 8 biogeographic realms and 14 major biomes. Each ecoregion is a large area with relatively uniform climate, vegetation, and distinct species communities. India has roughly 45–46 terrestrial ecoregions (Olson & Dinerstein, 2002), including "Himalayan Subtropical Pine Forests," "South Western Ghats Montane Rain Forests," and "Eastern Himalayan Broadleaf Forests." These ecoregions implicitly represent mountains through categories like "Montane Grasslands," "Tropical Montane Forests," and others. They provide a biologically meaningful, integrated framework of flora and fauna data that is consistent on a global scale for conservation. However, their limitations include being coarse for local use, having subjective boundaries, not directly incorporating physical terrain data, potentially lumping or splitting mountain systems, and being a static map not suited for land use or agriculture planning. WWF ecoregions connect mountains to ecological communities, highlighting biodiversity patterns and endemism (e.g., unique assemblages in Eastern Himalaya vs. Western Ghats), but they lack detailed topographic criteria and are primarily intended for conservation rather than agricultural or hydrological planning (Dinerstein *et al*., 2017).

3.1.3 | GMBA Mountain Inventory

The GMBA inventory (Körner *et al.*, 2017; Snethlage *et al*., 2022) offers a hierarchical, GIS-based global delineation of mountains. Version 2 (2022) includes about 8,616 named mountain ranges across multiple levels, with two spatial extents: Standard (core mountainous areas) and Broad (transitional slopes). For example, the Himalayas are divided into numerous ranges, such as the Great Himalayas, Kumaon Himalayas, and Karakoram. Strengths of the inventory include its detailed, updated, hierarchical, and scale-flexible data that is freely accessible, capturing known ranges and subranges, and being widely used in research. Its limitations include complexity, the need for GIS skills, overlapping polygons that complicate simple area calculations, and a focus on mountainous areas rather than non-mountainous hills. The inventory provides the most detailed global mountain map, linking terrain and biodiversity, and supports cross-scale comparisons. However, it may be excessive for general planning and still requires alignment with other frameworks, such as ecoregions or climate belts.

3.2 | Indian Frameworks

3.2.1 | Biographic Zones

Rodgers and Panwar (1988) classified India into 10 biogeographic zones based on overall biota and broad environmental differences, further dividing these into 27 provinces. Mountain-specific zones include the Trans-Himalaya (Zone 1), Himalaya (Zone 2), Northeast (Zone 9), and Western Ghats (Zone 5). These zones were created primarily for wildlife conservation, focusing on flora and fauna distributions. Strengths include an ecology-centered approach, reflection of historical biogeography (such as Gondwanan versus Laurasian affinities), and their simplicity and influence in protected area planning. However, they have limitations: being broad-brush, they overlook sub-national elevation variations, have coarse, somewhat subjective boundaries, are outdated (from 1988), were not initially GIS-based, and are less applicable to agriculture or watershed management. A key insight is that the zonation emphasizes India's main mountain and hill regions but combines diverse habitats — such as dry Ladakh and the lush Eastern Himalayas into a single "Himalaya" zone. While useful for summarizing biogeography, it offers limited detail on elevational gradients or local heterogeneity.

3.2.2 | Agro-ecological Zones (ICAR-NBSS&LUP)

In 1999, the NBSS division of ICAR identified 20 agroecological regions (AERs) by combining data on physiography, climate (growing period), and soils (NBSS&LUP, 1999). These regions represent broad production zones, such as AER-1 "Western Himalayas (cold arid)" and AER-17 "Northeastern Hills (warm perhumid)", and were intended to guide agricultural research and technology transfer. About 60 smaller agroecological sub-regions provide more detailed stratification. Strengths include focusing on key factors such as rainfall, soils, and season length, which are crucial for farming; making them more relevant for crop planning; and considering the interaction between climate and soils. Limitations include their design for agriculture rather than ecology, the possibility that a single region might encompass both lowland and highland areas if their growing periods (LGP) are similar, and their age, last formally updated in 1996. These zones are relatively large with limited ecological context. A key insight is that AEZs emphasize agro-climatic continuity but may divide mountain systems by cropping conditions rather than ecological coherence—for example, grouping the entire Western Ghats and nearby coastal plains into a single region based on similar rainfall and soil characteristics.

3.2.3 | Watershed/River-Basin Framework CWC/India-WRIS

India's river systems are organized hierarchically into basins, sub-basins, watersheds, and micro-watersheds (Central Water Commission [CWC], 2012 & 2014). The India-WRIS divides the country into 6 river regions, 35 basins, 112 catchments, 550 sub-catchments, and 3,257 watersheds ranging from 50 to 200 km². These river basins are categorized as Himalayan, Peninsular/Deccan, Coastal, and Inland Drainage rivers. Strengths include a terrain-based approach that is useful for water and flood planning, along with a detailed atlas and digital GIS data. Watershed boundaries naturally follow topographic divides in mountainous areas. However, the major concern is that the focus isn't on ecology or agriculture; mountain systems are divided by drainage patterns rather than continuous ecological zones, and boundaries can vary across watershed scales, potentially overlooking non-hydrological connections. Nevertheless, watershed mapping offers a hydrologic perspective on mountain regions—ideal for water resource management but less so for biodiversity or agricultural zones. For example, a single mountain ridge in the Western Ghats might drain to two different seas, resulting in separate basin classifications.

TABLE 1 Comparison of major classification frameworks relevant to hill and mountain ecosystems of India

Framework (Institutions)	Criteria/Data Used	Mountain Relevance	Application/Sector	Spatial Scale	Strengths/ Limitations
Kapos Mountain Classes (UNEP–WCMC/FAO)	Elevation, slope, local relief	Explicitly delineates mountain terrain globally	Biodiversity, SDG monitoring	Global; ~1 km DEM	Objective, reproducible; ignores climate/ecology
WWF Terrestrial Ecoregions (Olson et al., 2001)	Climate, vegetation, species endemism	Montane forests/grasslands (e.g., Himalayan broadleaf, WG evergreen)	Biodiversity conservation	Global (~867 ecoregions)	Biologically meaningful; coarse for local planning
GMBA Mountain Inventory (Körner et al., 2017)	DEM ruggedness + expert mapping	Full extent of mountain terrain; 8,616 named ranges	Mountain ecology, biodiversity research	Global, hierarchical	Highly detailed, complex, focused on ranges only
Biogeographic Zones (Rodgers & Panwar, 1988)	Flora/fauna, physiography	10 zones including Himalaya, WG, NE Hills	Conservation/wildlife planning	National (10 zones, 27 provinces)	Ecology-focused; dated; too broad for site-level use
Agro-ecological Regions (NBSSLUP, 1999)	Topography, soil, climate, LGP	AER-1 (W. Himalaya), AER-17 (NE Hills), AER-19 (WG)	Agriculture and land-use planning	National (20 regions, 60 subregions)	Agriculture-relevant; ignores biodiversity/forestry

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Table 1 continued

Framework (Institutions)	Criteria/Data Used	Mountain Relevance	Application/Sector	Spatial Scale	Strengths/ Limitations
Watershed Atlas (CWC, 2012)	Hydrology (drainage divides)	Himalayan/Peninsular river basins	Water resources and development	National (6 regions to micro-watersheds)	Physically rigorous; splits ecological continuity
LULC Maps (NRSC/ISRO)	Remote sensing imagery	Alpine grassland, Snow/Glacier, Ravines classes	Land-use planning baseline	National (1:50k)	Detailed; infrequently updated
Forest Type Maps (FSI, 1987)	Forest community/structure	Himalayan moist temperate, Sub-tropical pine, etc.	Forestry planning	National (4 groups × 32 types)	Illustrative; dated
FAO Global AEZ	Climate, soils, land suitability	Aligns with national AERs	Agriculture, food security	Global	Mirrors NBSS AERs for India

3.2.4 | Land-Use/Land-Cover Maps (NRSC, ISRO)

The national LULC mapping (e.g., 2016–2020) uses satellite imagery to classify land at 1:50k scale (NRSC, ISRO). Hill-specific categories include *"Alpine/Sub-Alpine Grassland," "Snow and Glaciers,"* and *"Gullied/Ravinous Land."* Together, these classes capture both natural cover (forest, grassland) and anthropogenic use (cropland terraces, settlements) and serve as a primary input for any land-use planning.

3.3 | Integrated Discussion: Global vs. Indian Frameworks

The global schemes and Indian schemes each emphasize different aspects of mountain lands. The Kapos/UNEP classes and GMBA inventory use physical criteria (elevation, slope, relief) to objectively identify mountain terrain, whereas the WWF ecoregions use ecological-historic criteria (species assemblages and climate). Indian frameworks are context-specific: Rodgers–Panwar biogeographic zones emphasize India's distinct biogeographic histories; agro-ecological zones emphasize agriculture-related climate-soil factors; and watershed basins emphasize hydrology. For example, the Himalayan region is treated in multiple ways: Rodgers–Panwar designate it as a single "Himalaya" zone; WWF identifies at least six Indian ecoregions from alpine shrublands to subtropical forests; GMBA lists dozens of named ranges; AEZ splits the region by growing season; and the Watershed Atlas splits it by river basins (Indus vs. Ganga vs. Brahmaputra). Each framework offers a different but equally valid "lens." A critical insight from a synthesis is that no single map suffices for Himalayan or broader hill issues. Conservationists may overlay WWF ecoregions and GMBA ranges to identify biodiversity hotspots, while agricultural planners rely on AEZs and watershed units to design interventions. Effective conservation or planning will overlay and cross-reference these maps. The choice of framework depends on purpose: WWF ecoregions emphasise biodiversity patterns; AEZs emphasise crop-climate suitability; and watersheds emphasise drainage connectivity.

4 | THE INDIAN HIMALAYAS: CLASSIFICATION, ECOLOGY, AND PRODUCTION SYSTEMS

The Indian Himalayas are geographically divided into two primary flanks: The Western Himalayas and the North-Eastern Himalayas (NEH), collectively covering 14 states and 90 districts.

- **Western Himalayas:** This region constitutes 62.4% of the total Himalayan area, characterized by steep slopes, severe winters, and predominantly coniferous forests. It includes Jammu & Kashmir, Ladakh, Himachal Pradesh, and the hill regions of Uttarakhand.
- **North-Eastern Himalayas:** Defined by relatively gentler slopes, high rainfall, and a humid climate, this region includes Arunachal Pradesh, Sikkim, and Meghalaya.

The divergence between classification frameworks is especially instructive in the Himalayan context. Rodgers and Panwar (1988) assign the entire range to one or two zones (Trans-Himalaya, Himalaya), so policy documents often treat "Himalaya" as a single unit. WWF (Olson *et al*., 2001) identifies at least six Indian ecoregions across the range — from alpine shrublands to subtropical forests — underscoring its ecological complexity. The GMBA inventory (Snethlage *et al*., 2022) further delineates dozens of named sub-ranges (e.g., Great Himalaya, Kumaon Himalaya, Karakoram). AEZs (NBSS&LUP, 1999) break the range into regions by climate: far-north Ladakh is "cold dry" (Region I) while eastern slopes fall under "Eastern Himalayas" (Region XVI). The Watershed Atlas (CWC, 2012) splits the range by drainage — Indus for Ladakh/Karakoram, Ganges for Garhwal and Kumaon, and Brahmaputra for Arunachal/Assam. Each scheme is valid for its goal: WWF/GMBA emphasises high levels of endemism between the Eastern and Western Himalayas, AEZ emphasises crop-growing challenges at altitude, and watershed maps serve hydropower and flood-control planning.

Himalayan ecosystems are defined by fragility, marginality, and poor accessibility (Singh *et al*., 2011). The wide variation in altitude and latitude generates a vast diversity of microclimates, habitats, and vegetation. Approximately 15% of the area is under permanent snow, providing a perennial flow of roughly 1,204 km³ annually to the Indo-Gangetic plains (Singh *et al*., 2011). Despite this abundance, the western region faces acute water scarcity during summer (Table 2). The ecosystem is under severe threat from excessive exploitation due to increasing human and livestock populations; activities such as mining and road construction in fragile areas lead to mass soil erosion and heavy sedimentation of downstream reservoirs (Negi & Joshi, 2002; Xu *et al*., 2009). Livelihood systems vary spatially based on altitudinal zones:

- **Sub-montane/Low-hill Zone:** Focuses on rice, maize, wheat, citrus, mango, and livestock such as buffaloes.
- **Mid-hill Zone:** Predominantly an agri-horti-livestock system involving maize, wheat, citrus, pineapple, and banana.
- **Dry Temperate Zone (>2,200 m):** Dominated by sheep, goats, and yak. Migratory or nomadic pastoralism is a traditional practice to maintain ecosystem integrity.
- **Western Region Specialisation:** Apples are the major horticultural crop; off-season vegetables (peas, tomato) are widely cultivated.
- **NEH Region Specialisation:** Shifting cultivation (Jhum) is still practiced; high-value crops include spices, condiments, pineapple, and banana (Tripathi & Barik, 2003; Tiwari *et al.*, 2010).

TABLE 2 Synthesis of Strengths, Weaknesses, Opportunities, and Threats (SWOT) for Indian Himalayan hill ecosystems.

Category	Key Findings
Strengths	Enormous wealth of natural resources (land, water, vegetation) and rich indigenous knowledge systems.
Weaknesses	Poor infrastructure, subsistence-oriented economy, and lack of situation-specific modern technologies.
Opportunities	Potential for high-density orcharding, cold-water aquaculture (Mahaseer), and value-added agroforestry interventions.
Threats	Resource degradation, unauthorised migration, loss of genetic diversity in local crops, and increasing highland–lowland conflicts.

TABLE 3 Major geospatial data sources for hill and mountain ecosystem mapping in India

Data Type	Source/Resolution	Coverage & Use	Indian Example/ Agency
Digital Elevation Model	SRTM (~30 m); ASTER (~30 m); Cartosat-1 DEM (30 m)	Elevation, slope, aspect, ruggedness — delineating altitude zones and hillslopes	ISRO Cartosat DEM
Climate	IMD (rainfall grids, ~25 km); WorldClim/CHELSA (~1 km)	Rainfall, temperature, season length — defining climate belts	IMD State Centre; ICAR climate zones
Soils	NBSS&LUP soil map (1:250k); SoilGrids (250 m)	Soil orders, texture, depth — affecting fertility and erosion risk	NBSS&LUP soil maps and AER charts
Land Cover	NRSC LULC maps (1:50k); MODIS (500 m); ESA-CCI (300 m)	Vegetation and land-use classes (forests, grasslands, agriculture, built-up)	NRSC Bhuvan portal
Vegetation/Ecoregions	FSI forest type map; UNEP ecoregions dataset	Broad vegetation zones (montane forest, dry forest, etc.)	FSI Report (1987) forest atlas
Hydrology/Watersheds	River network GIS; Watershed Atlas polygons	Drainage divides — organising units by catchment	India-WRIS GIS (CWC, 2012)
Socio-economic	Census 2011 (district/tehsil); Tribal map; Road network	Population density, land-use pressure, infrastructure	Census of India; Ministry of Tribal Affairs
Remote Sensing	Landsat, Sentinel imagery; Google Earth; field surveys	Satellite imagery for validation; local data (crop, micro-topography)	NRSC ground truth programmes

5 | PROPOSED MULTI-CRITERION FRAMEWORK FOR HILL AND MOUNTAIN EPUS

To define **Ecological Production Units (EPUs)** in Indian hill regions, we propose a GIS-based, hierarchical multi-criteria framework (Table 3). The key steps are as follows.

Step 1 — Initial Stratification: Use existing broad divisions to define the analysis extent, separating the country into major mountain complexes: Western Himalaya, Eastern Himalaya, Central Indian Highlands, Western Ghats, Eastern Ghats, and NE Hills (Fig. 2). These align broadly with WWF ecoregions or biogeographic provinces (Rodgers & Panwar, 1988; Olson *et al*., 2001).

Step 2 — Variable Selection: Compile layer data including DEM (elevation, slope), climate (rainfall, temperature, growing period), soils (texture, depth), land cover, and socio-economics (population, livelihoods). Where available, include disturbance and hazard layers (landslide susceptibility, fire risk).

Step 3 — Criteria Derivation: For each pixel or watershed unit, compute derived indicators:
- Elevation band (e.g., 0–500 m, 500–1,500 m, >1,500 m)
- Slope category (e.g., <15°, 15–30°, >30°)
- Rainfall regime (e.g., >2,000 mm/yr, 1,000–2,000 mm/yr, <1,000 mm/yr)
- Length of Growing Period (LGP in days)
- Soil depth class (deep vs. shallow)
- Land cover type (dense forest, open forest, grassland, agriculture)
- Population pressure (e.g., low <50/km², medium, high)
- Accessibility (distance to roads or towns)

Step 4 — Homogeneity Analysis: Group areas similar across these indicators using:
- *Clustering algorithms:* K-means or hierarchical clustering on a multi-dimensional normalised feature space;
- *Overlay and rule-based grouping:* Pre-define classes (e.g., all pixels with >2,000 m, >30° slope, and <800 mm rain as "high alpine zone");
- *Principal Component Analysis (PCA):* Reduce dimensionality, then classify principal components.

Step 5 — Refinement and Expert Review: Check candidate EPU maps for ecological coherence; merge small fragments with adjacent units where conditions are similar; adjust boundaries to align with natural features (ridges, rivers) or administrative units for practicality.

Step 6 — Validation: Compare EPUs with independent data (e.g., vegetation maps, known farming practices). Each EPU should ideally correspond to a consistent set of dominant tree species or crop systems. Field surveys and local expert input — including participatory GIS with tribal and rural communities — can refine the units (Tiwari *et al*., 2010).

FIGURE 2 Different mountain regions of India

Step 7 — Scale Tiers: Produce EPUs at multiple scales — coarse units of 100–1,000 km² for landscape planning, and finer subunits of 10–50 km² for local watersheds — nested so that coarse units aggregate to ecoregions and fine units align with micro-watersheds.

High-altitude catchments (>3,500 m) with glaciers form a *"Glacial Alpine"* EPU, characterised by permanent snow cover, sparse vegetation, and meltwater provisioning. Mid-montane forests (2,000–3,500 m, high rainfall, brown forest soils) form a *"Subalpine Broadleaf"* EPU. Lower rain-shadow slopes (<1,500 m, <800 mm) form a *"Dry Temperate"* EPU. Each has distinct production potential: alpine pastures, oak forests, and chestnut forest, respectively. Across the country, analogous sets of EPUs would be delineated for each mountain system.

5.1 | Application to Planning and Climatic Adaptation

Once EPUs are mapped, they can inform multiple planning domains. In watershed management, EPUs identify zones with similar erosion risk and land use; for example, an EPU designated "steep degraded mid-hills" might be prioritised for terracing, afforestation, and rainwater harvesting. In agroforestry, EPUs match species to ecological suitability: Shisham (*Dalbergia sissoo*) might suit lower humid EPUs, while pine or fir suits cooler, higher EPUs. In conservation zoning, EPUs can target high-endemism areas — for example, an EPU corresponding to the "Shola-grassland mosaic" in the Nilgiris. For climate adaptation, EPUs with limited moisture or short growing seasons can be prioritised for drought-resistant cropping trials. In policy, EPUs could integrate multiple schemes. MGNREGA (Mahatma Gandhi National Rural Employment Guarantee Act) could allocate soil conservation funds based on EPU vulnerability. State horticultural boards could use EPU maps to diversify hill agriculture. The National Mission for Himalayan Studies (NMHS) and "Sub-Mission on Himalayan Ecosystems" under India's National Action Plan on Climate Change could adopt EPU mapping as a decision-support tool.

6 | GAPS AND RECOMMENDATIONS

Despite these opportunities, significant gaps remain. NBSS soil maps are at 1:50,000, and some regions lack detailed surveys. LULC maps are updated infrequently. Climate change impacts — shifting rainfall patterns, glacial retreat (Xu *et al*., 2009) — are seldom integrated into static zonations. Socio-economic mapping (livelihood zones, land ownership) is weakly linked to ecological units. Many existing classifications were designed pre-GIS and are not easily digitised. Institutional silos (agriculture vs. forestry vs. water) mean no single agency owns the EPU concept. Methodologically, automated classification can be challenged by subjectivity in variable weighting or cluster number selection, and local variability (microclimates, ethnic land practices) may not be captured.

We propose the following priority actions:

1. **Update and integrate geospatial data**: Release high-resolution DEM (IIRS Cartosat SRTM); expand soil and forest inventories with new field sampling and remote sensing (e.g., LiDAR for canopy).
2. **Develop standardised EPU guidelines**: Pilot EPU mapping in one Himalayan state (MoEF/NBSS&LUP leadership) to refine criteria.
3. **Link EPUs to monitoring**: Tie forest cover change or groundwater depletion indicators to each EPU.
4. **Encourage interdisciplinary research**: Combine geography, ecology, and social science — for example, incorporating community land tenure (Tiwari *et al*., 2010).
5. **Use participatory GIS**: Involve local stakeholders, including tribal communities, in validating EPU maps.
6. **Policy mainstreaming**: Mandate use of EPU-level analysis in watershed management plans, hill area development programmes, and adaptation planning.
7. **Human Resource Development**: Empower women, who constitute the primary agricultural workforce in Himalayan regions (Planning Commission, Government of India, 1989).
8. **Technology Refinement:** Develop stress-resistant crop varieties and localised water harvesting systems appropriate to specific EPU conditions.

7 | CONCLUSIONS

Hill and mountain ecosystems in India are complex mosaics of soils, climates, and communities. Traditional maps — states, districts, broad agro-climatic zones — do not capture this heterogeneity. As demonstrated in this review, multiple Indian and international frameworks exist that stratify landscapes by ecological factors. The Himalayan region, for example, is simultaneously a single biogeographic zone (Rodgers & Panwar, 1988), six or more ecoregions (Olson *et al*., 2001), dozens of named mountain ranges (Snethlage *et al.*, 2022), two agro-ecological regions (NBSS&LUP, 1999), and three major river basins (CWC, 2012) -each perspective revealing distinct but complementary information.

A gap remains in *integrating* these approaches into a single, operational mapping of homogeneous Ecological Production Units. The multi-criteria GIS framework proposed here — combining topography, climate, soils, cover, and human data — can sharpen the focus of conservation and development: directing soil conservation to the most erosion-prone units, matching crop and forest types to suitable zones, and targeting climate adaptation to vulnerable hill strata. The approach aligns with global ecosystem-based management practices (FAO, 2007) while being tailored to Indian data and policy contexts.

For next steps, pilot studies are needed (e.g., mapping EPUs in a Himalayan state or the Western Ghats). The scientific community should work with government agencies (forest, agriculture, environment ministries) to harmonise terminology and data standards, perhaps through a national "Hills GIS" database. Given accelerating pressures on upland ecosystems, there is an urgency to refine and apply these mapping frameworks. Ultimately, delineating homogeneous ecological production units can make land management in India's hills more targeted, efficient, and resilient.

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CONFLICT OF INTEREST

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

DATA AVAILABILITY STATEMENT

Data will be made available on the request.

AUTHOR'S CONTRIBUTION

Rajive K. Singh: Conceptualization, Investigation, Formal analysis, Writing - original draft, Review & editing. Raman Jeet Singh: Review & editing, Formal analysis, Writing - original draft.

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