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Integrated Watershed Management Strategies For Sustainable Development: A Case Study Of Chargad Microwatershed In Pauri District, India

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Abstract
The progressive degradation of small mountainous watersheds in the mid-Himalayan region poses a critical threat to regional water security, soil productivity, and rural livelihoods. This study presents a GIS and remote sensing-based integrated assessment of the Chargad Microwatershed in Pauri Garhwal District, Uttarakhand, India, to formulate spatially targeted watershed management strategies for sustainable development. High-resolution satellite imagery and DEM data in a GIS framework to assess the physical and socio-economic status of the microwatershed. Field surveys and Participatory Rural Appraisal (PRA) were integrated with geospatial analysis to incorporate socio-economic dimensions. Results indicate that 64% of the area has steep slope and 39.5% falls in high-to-very-high erosion risk zones, particularly in deforested and barren areas. Forest cover (~48% of area) is largely degraded (only ~1.2% very dense canopy), contributing to runoff and sedimentation Twenty-one spring water sources (naulas and dharas), several exhibiting declining discharge trends, were geo-referenced across the watershed. Based on the integrated analysis, this study proposes a spatially explicit, multi-pronged watershed management framework encompassing structural soil and water conservation measures, afforestation and spring-shed development, sustainable agricultural intensification, and community-based institutional strengthening. The study underlines the need for combining scientific tools with community-led planning to enhance watershed resilience. Key findings and management strategies from this case study have relevance for other mid-Himalayan catchments aiming to achieve Sustainable Development Goals through climate-smart watershed initiatives.

Keywords: *Watershed management; GIS; Remote sensing; NDVI; DEM; Land use/land cover; Erosion intensity; Spring rejuvenation; Soil and water conservation; Sustainable development*

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I. Introduction

Watershed management has emerged as one of the most effective approaches to sustainable natural resource governance, particularly in ecologically fragile and topographically complex regions such as the Indian Himalayas. A watershed or catchment is a topographically delineated hydrological unit within which surface runoff converges to a common outlet, integrating land, water, vegetation, and human systems in a spatially coherent and administratively tractable unit suited for integrated planning and management (Wang et al., 2016).

India, with its extensive watersheds, has prioritized watershed management through successive national programs (DPAP, DDP, IWDP, IWMP etc.) that emphasize soil conservation, rainwater harvesting, and afforestation (Nagaraja & Ekambaram, 2015). However, many programs remained technology-driven with limited community involvement, leading to suboptimal outcomes. In recent years, watershed management in India has shifted toward participatory, climate-smart strategies that leverage modern tools (e.g. RS/GIS, RUSLE modeling) and address livelihood concerns (Jat et al., 2025)

Uttarakhand, situated in the central Himalayan region, presents a uniquely challenging yet critically important context for watershed management. Its rugged terrain, geologically young and tectonically active slopes, spatially variable but intense monsoonal precipitation, complex multi-strata land-use systems, and high dependence of rural communities on ecosystem services from spring-fed water sources make it a priority landscape for integrated watershed interventions. The region has experienced accelerating ecological stress over recent decades: increasing frequency of extreme rainfall events (cloudbursts, flash floods), progressive deforestation and land use change on slopes, declining spring discharges attributed to recharge zone degradation, and diminishing agricultural productivity accompanied by widespread rural out-migration (Chauhan, 2010). These interconnected stresses demand a comprehensive, spatially targeted approach to watershed planning that conventional, structure-centric interventions have proven insufficient to deliver.

Remote sensing (RS) and Geographic Information Systems (GIS) have revolutionized watershed assessment and planning by enabling spatially accurate, cost-effective, and temporally repeatable characterizations of biophysical resources across inaccessible terrain (Ozesmi & Bauer, 2002). The integration of high-resolution satellite imagery, digital terrain models, and participatory socio-economic data within a GIS analytical framework enables comprehensive resource inventories, erosion vulnerability assessments, and spatially targeted intervention mapping that manual survey methods cannot efficiently achieve at the watershed scale. This geospatial approach has become particularly critical in mid-Himalayan watersheds, where complex topography, limited road access, and high spatial heterogeneity in biophysical conditions necessitate digital spatial analysis as the primary characterization methodology (Rai et al., 2017; Sharma et al., 2023).

II. Study Area

The Chargad Microwatershed (MWS) is situated in the Pokhra Development Block of Pauri Garhwal District, Uttarakhand, India, extending between 29°50'11.08″ N to 29°57'4.47″ N latitude and 78°54'42.43″ E to 78°56'6.9″ E longitude (Figure 1). The watershed covers a total geographical area of approximately 1,395.51 hectares and drains into the Machhlad sub-watershed, forming a critical ecological and hydrological unit within the mid-Himalayan zone. It is bounded by Basol Gad to the north, Syoti Gad to the east, the Kandali Nadi Microwatershed to the south, and the Saintoligad Microwatershed to the west. The MWS encompasses five Gram Panchayats (GPs) Gadri, Dwila Talla, Jhalpadi, Salan, and Chopda comprising six revenue villages.

Geologically, the watershed is underlain by Garhwal Group rocks of the Lesser Himalayan zone, predominantly comprising granitic, dolerite, and quartzite formations. Soils are predominantly sandy loam to loamy in texture, varying in depth and organic matter content across the altitudinal gradient from shallow lithic soils on steep upper slopes to relatively deeper, more productive soils on lower terraced fields and valley floors. The elevation ranges from approximately 1,000 m to 2,650 m above mean sea level (amsl), encompassing sub-montane, mid-montane, and upper-montane ecological zones within a comparatively small spatial extent, a feature that generates exceptional within watershed heterogeneity in climate, soil, vegetation, and land-use conditions.

The climate is broadly monsoonal-temperate: the lower reaches experience summer maxima of 35–40°C, while frost conditions prevail in the upper zones during winter months. Monsoonal precipitation, concentrated between June and September, is substantial but spatially variable. Intense rainfall events on steep, partially vegetated slopes frequently trigger landslides, gully erosion and accelerated sediment transport. The dominant forest types are Ban Oak (Quercus incana) and Himalayan Chir Pine (Pinus roxburghii), with mixed coniferous and upper oak-fir assemblages at higher elevations, consistent with the mid-altitude zonation documented for the Garhwal Lesser Himalayas (FSI, 2021). These socio-economic and physical characteristics make Chargad MWS a representative case for mid-Himalayan watershed management challenges and for testing integrated interventions.

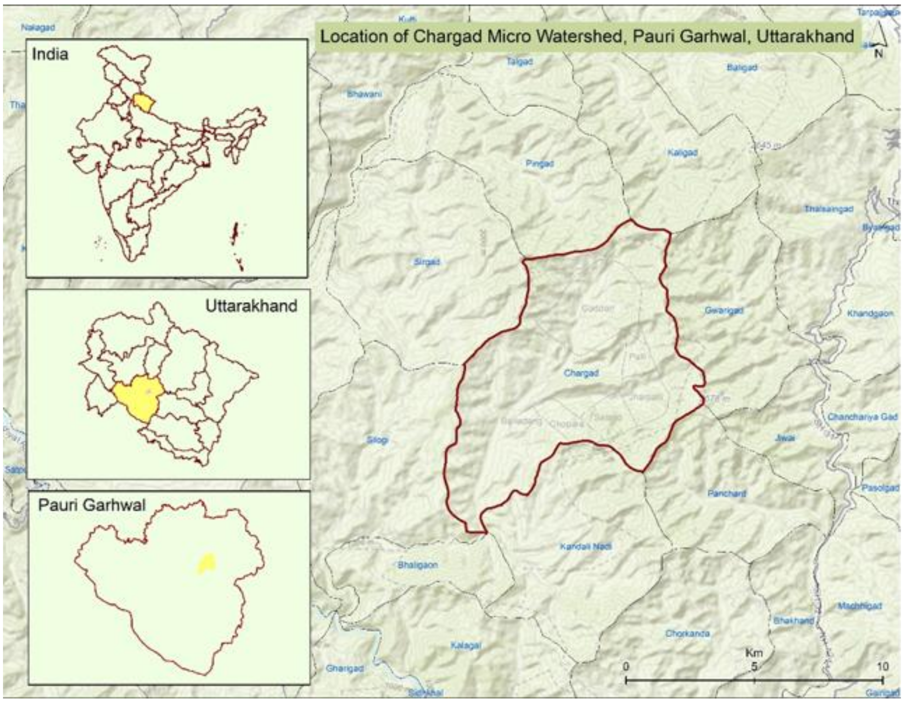

Figure 1: Location Map of Chargad MWS, Pauri Garhwal, Uttarakhand, India

III. Review Of Literature

Integrated watershed management (IWM) has evolved substantially from its origins in engineering-focused soil and water conservation toward a comprehensive, systems-based approach encompassing ecological restoration, livelihood enhancement, climate adaptation, and participatory resource governance (Wang et al., 2016; Jat et al., 2025). This evolution has been driven by growing recognition that hydrological processes within a watershed are inseparably linked to land-use decisions, socio-economic conditions, and institutional governance structures — none of which can be effectively managed in isolation (Nagaraja & Ekambaram, 2015).

In India, early watershed programs including the Drought Prone Area Programme (DPAP), Desert Development Programme (DDP), Integrated Wasteland Development Programme (IWDP), and National Watershed Development Project for Rainfed Areas (NWDPRA) were primarily focused on soil conservation, runoff management, and afforestation. These programs were frequently critiqued, however, for fragmented planning, limited community participation, and inadequate integration of socio-economic dimensions (Bhan, 2013). The subsequent transition toward participatory and integrated approaches, culminating in the Integrated Watershed Management Programme (IWMP, 2009) with its Common Guidelines emphasizing decentralized planning and livelihood integration, reflected accumulated learning from three decades of programmatic experience.

The application of RS and GIS technologies has fundamentally transformed watershed characterization, prioritization, and intervention planning. Digital Elevation Model (DEM)-based terrain analysis enables automated extraction of drainage networks, slope gradients, aspect distributions, and morphometric parameters that previously required extensive and costly field surveys (Lai et al., 2016). Morphometric analysis encompassing drainage density, bifurcation ratio, elongation ratio, stream frequency, and relief ratio has been widely demonstrated to support sub-watershed prioritization for conservation treatment (Rai et al., 2017; Balasubramanian et al., 2017; Sutradhar & Mondal, 2023). In Himalayan contexts specifically, where terrain complexity and inaccessibility severely constrain conventional field surveys, GIS-based spatial analysis serves as the primary characterization methodology.

Land use/land cover (LULC) mapping using multi-spectral satellite imagery has become indispensable for tracking vegetation dynamics, land degradation trajectories, and changes in watershed hydrological behavior over time. Spectral vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI), provide sensitive measures of vegetation health and canopy density that correlate strongly with runoff generation, infiltration capacity, and soil erodibility (Sharma et al., 2023). Studies in Himalayan watersheds consistently demonstrate that declines in NDVI values are associated with increased erosion risk, reduced groundwater recharge, and diminished baseflow maintenance of perennial streams and springs.

Soil erosion assessment using composite overlay approaches integrating slope, vegetation cover and land-use data aligned with the methodologies recommended by ICAR-IISWC (formerly CSWCRTI) provides a practical, data-efficient framework for identifying critical erosion zones in data-scarce mountain settings (Samra et al., 2000; Sharda et al., 2013). The more quantitative RUSLE (Revised Universal Soil Loss Equation) model, when implemented within a GIS environment, generates spatially distributed erosion risk surfaces that enable precision targeting of conservation investments (Balasubramani et al., 2015; Mahapatra et al., 2018). GIS-based multi-criteria analysis has further been applied to identify optimal sites for check dams, percolation tanks, and groundwater recharge structures in Himalayan watersheds, improving the efficiency of structural interventions (Al-Adamat et al., 2010; Kadam et al., 2012).

Spring water sources locally known as naulas and dharas in the Garhwal Himalayan tradition represent the primary domestic and agricultural water supply for millions of rural households in the mid-hills of Uttarakhand. Declining spring discharges, attributed to the combined stresses of deforestation of recharge zones, land-use change from perennial to seasonal vegetation, groundwater over-abstraction, and shifts in monsoon precipitation patterns, constitute an increasingly documented and severe livelihood crisis across the Indian Himalayan Region (Chauhan, 2010). Springshed management, which delineates subsurface recharge zones and designs land-use interventions to sustain recharge, is increasingly recognized as a critical extension of conventional watershed management in spring-dependent mid-Himalayan landscapes, yet remains under addressed in the academic literature.

Participatory Rural Appraisal (PRA) and community-based planning approaches have been demonstrated to significantly enhance both the effectiveness and sustainability of watershed interventions. Meta-analyses of Indian watershed programs consistently find that participatory management enhances ecosystem service generation relative to top-down, externally-driven approaches (Joshi et al., 2004; Mansuri & Rao, 2004). The integration of indigenous knowledge, particularly regarding traditional water harvesting technologies and seasonal resource-use patterns, with modern geospatial analysis frameworks represents an important frontier for developing culturally appropriate and institutionally sustainable management strategies in complex social-ecological systems such as Chargad MWS.

IV. Materials And Methods

Data Sources: IRS LISS-IV multispectral imagery (spatial resolution: 5.8 m; bands: green, red, near-infrared) was utilized for LULC classification and NDVI computation. Cartosat DEM (Version 3; spatial resolution: 30 m) derived from ISRO's Cartosat-1 stereo satellite was employed for terrain analysis, drainage network extraction, and hydrological modeling. The DEM was pre-processed through sink-filling and flow direction computation prior to hydrological analysis. Village boundaries were obtained from the Survey of India. Socio-economic data were sourced from Census 2011 and gram panchayat records. Traditional spring water source (naula/dhara) data were collected through systematic field surveys using GPS instruments and semi-structured community interviews. Forest type and density data were obtained from the Forest Survey of India (FSI) and cross-referenced with satellite imagery classification.

Software and Analytical Tools: Spatial analyses were conducted using ArcGIS (ESRI) for stream network extraction, thematic mapping, and erosion intensity overlay; ERDAS Imagine for satellite image processing, supervised-unsupervised hybrid LULC classification, and NDVI computation; and QGIS 3.x for complementary overlay analyses and cartographic output. GPS data from field surveys were integrated into ArcGIS for spring source geo-referencing and validation. Accuracy assessment of the LULC classification was performed using a confusion matrix with ground-truth points collected during field visits and cross-validated against Google Earth high-resolution imagery.

Terrain and Drainage Analysis: The Cartosat DEM was processed in ArcGIS using the standard hydrological modelling. Elevation, Slope and Aspect were derived from DEM and classified into standard classes (SLUSI nd). The drainage network was extracted and stream ordering was performed using the Strahler (1952) hierarchical method, wherein two streams of the same order merge to form a stream of the next higher order.

LULC Mapping and NDVI Analysis: A hybrid supervised-unsupervised classification approach was applied to the IRS LISS-IV imagery. Initial unsupervised clustering (ISODATA algorithm) established preliminary spectral classes, which were subsequently refined through supervised maximum likelihood classification using training samples collected from field surveys and high-resolution Google Earth imagery. Forest density was classified using the FSI canopy cover convention: very dense forest (≥70% canopy cover), moderately dense forest (40–70%), and open forest (10–40%). NDVI was calculated as:

$$NDVI = (NIR - Red) / (NIR + Red)$$

where NIR represents the near-infrared band reflectance (Band 4: 0.77–0.86 µm) and Red represents the red band reflectance (Band 3: 0.62–0.68 µm).

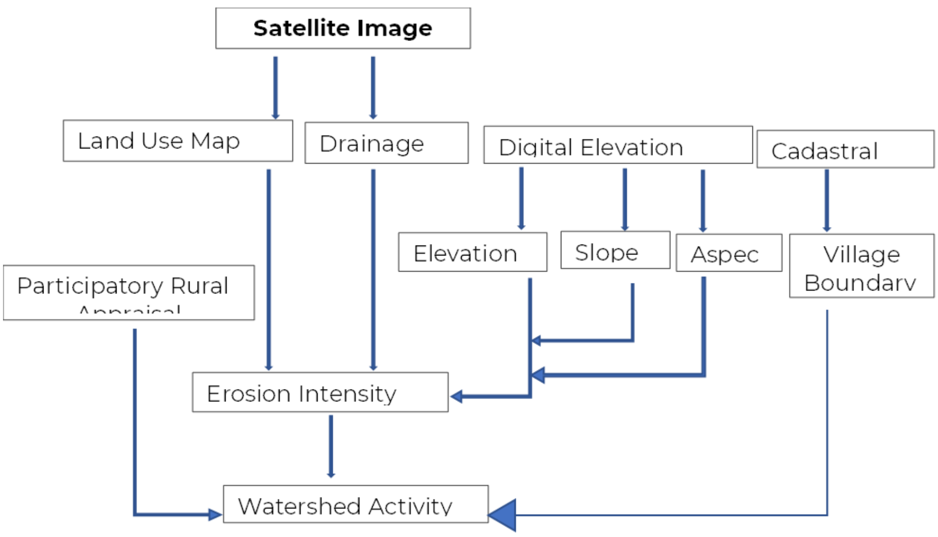

Figure 1: Flowchart of Watershed activity

Erosion Intensity Assessment: Erosion intensity was assessed through a weighted composite overlay of three thematic layers forest canopy density, LULC, and slope gradient using the methodology recommended by CSWCRTI, Dehradun (Samra et al., 2000; Sharda et al., 2013, Vatsa et al). Each layer was reclassified into a standardized erosion-risk rating, and the composite map was reclassified into four erosion risk categories: Low (E1), Moderate (E2), High (E3), and Very High (E4). This approach provides a practical, data-efficient qualitative erosion risk assessment framework appropriate for the data availability constraints of the study area.

Spring Water Source Survey: Traditional water sources, naulas (traditional stepped-stone spring enclosures), dharas (open flowing springs), and perennial stream sources within reserved forest compartments were systematically inventoried through structured field surveys. Source locations were geo-referenced using handheld GPS instruments. Discharge rates were measured at peak (post-monsoon) and lean (pre-monsoon) seasons using the volumetric (bucket-and-stopwatch) method.

Participatory Rural Appraisal and Activity Mapping: Participatory Rural Appraisal (PRA) was conducted in all five Gram Panchayats, employing techniques including focus group discussions, community resource mapping, seasonal calendars, and transect walks. PRA findings were integrated with geospatial analysis to ensure that proposed management interventions were both technically sound and socially feasible. Watershed management activity mapping, delineating proposed locations for structural conservation measures, plantation zones, and spring-shed protection areas was conducted using cadastral maps and satellite imagery as base layers, cross-referenced with PRA derived community knowledge of degradation hotspots and water source recharge areas (figure 2).

V. Results And Discussion

Terrain Characteristics: Chargad MWS is predominantly a mid-montane to sub-montane landscape with considerable altitudinal heterogeneity. The greatest areal proportion (44.81%) of the MWS lies in the 1,500–2,000 m elevation band, followed by 33.82% below 1,500 m, 20.93% in the 2,000–2,500 m band, and a mere 0.44% above 2,500 m. This altitudinal distribution has significant hydrological and land-use implications. Slope analysis reveals that steep terrain (>50%) dominates 46.7% of the MWS, while moderate slopes (33–50%) account for approximately 20%, and gentle slopes (<33%) constitute approximately 32% of total area. The prevalence of steep and very steep terrain (slopes >50%) implies fundamentally high geomorphic work potential and rapid runoff generation during monsoon events, consistent with the fragile terrain characterization of mid-Himalayan Lesser Himalayan watersheds reported by Mahapatra et al. (2018) for Uttarakhand. Aspect analysis indicates a broadly balanced distribution among the eight cardinal directions, though south- and southwest-facing slopes exhibit greater solar radiation receipt, lower soil moisture retention, and heightened moisture stress during dry periods that favour more drought-susceptible vegetation communities and increase fire risk, consistent with findings from comparable Himalayan microwatershed studies.

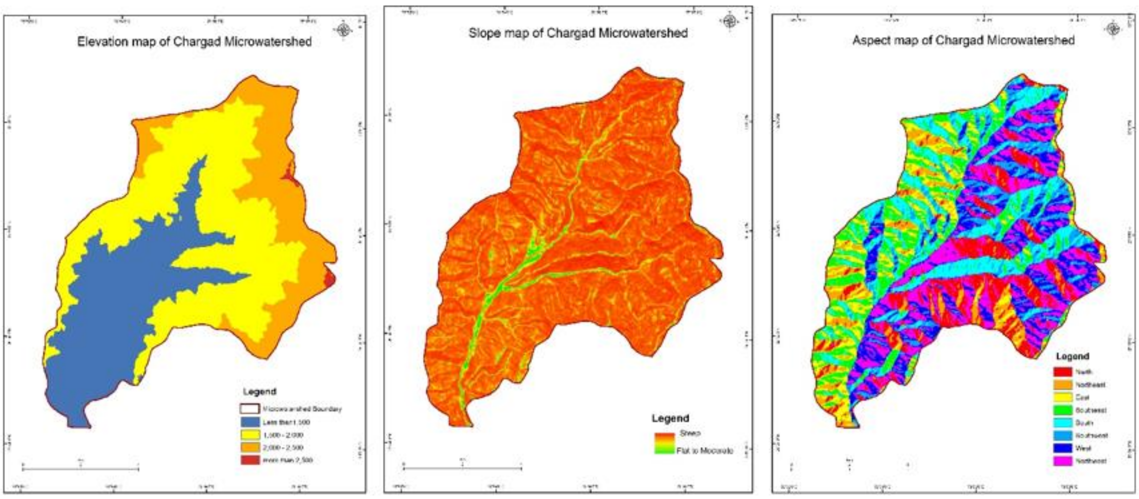

Figure3: Erosion, Slope and aspect maps of charged MWS

5.2 Drainage Morphometry and Hydrological Characterization: The drainage network extracted from the DEM exhibits a dendritic to sub-dendritic pattern, characteristic of relatively homogeneous geological formations (granitic and quartzitic) with moderate structural control. Stream ordering by the Strahler (1952) method identified a fourth-order drainage basin comprising 106 first-order, 54 second-order, 27 third-order, and 2 fourth-order stream segments, for a total of 189 streams (Table 1). The high number of first-order streams relative to higher-order segments reflects an elevated drainage density, which leads to limited permeability and steep gradients. The morphometric signature is consistent with the concentrated gully erosion and sediment transport observed in the main drainage axes (figure 4). These findings show the similar morphometric characterization of Himalayan microwatersheds observed by Rai et al. (2017) and Sutradhar and Mondal (2023), who identified this as a reliable indicator of accelerated runoff and erosion susceptibility.

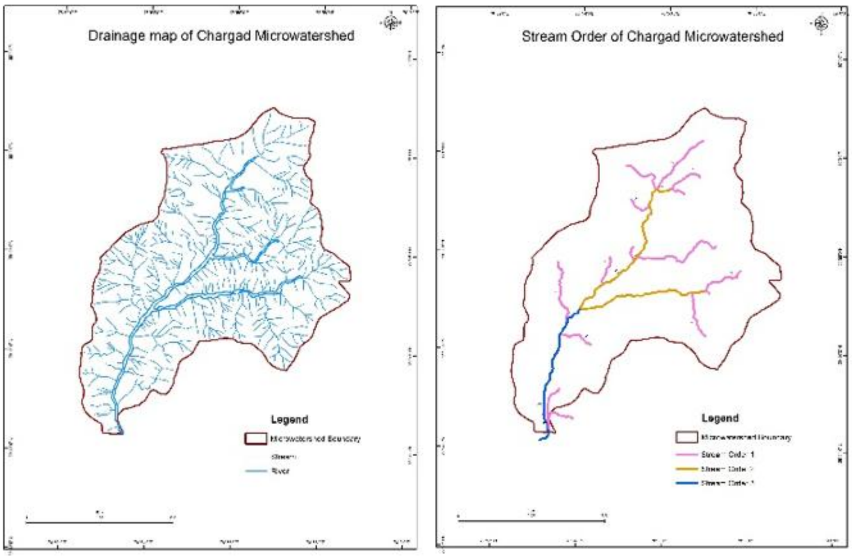

Figure 4: Erosion, Slope and aspect maps of charged MWS

Table 1: Strahler stream order classification of the Chargad Microwatershed drainage network.

Stream Order	No. of Streams	Bifurcation Ratio	Hydrological Characteristics	Management Significance
1st	106	—	Headwater; no tributaries; primary recharge contributors	Priority spring-shed protection zones
2nd	54	1.96	Seasonal; significant sediment transport	Bush/stone check dams recommended
3rd	27	2.00	Semi-perennial; active bank erosion	Crate-wire check dams; spurs
4th	2	13.5	Main drainage; perennial; outlet channels	Bank protection; riparian buffer strips
Total	**189**	—	—	—

Land Use/Land Cover Analysis: The LULC mapping of the Chargad Microwatershed reveals that the forest land is the dominant land-use category, with evergreen and semi-evergreen forests occupying 41.12% of the total area, followed by scrub forests (3.65%) and deciduous forests (3.25%), together comprising a total forest cover of approximately 48.02% of the watershed (Table 2). Agricultural cropland accounts for 30.61% of the total MWS area, reflecting the strong dependence of all five Gram Panchayats on subsistence-oriented hill agriculture, primarily rainfed cultivation of millets, pulses, wheat, and off-season vegetables on terraced slopes at lower and mid-altitudes (Figure 5).

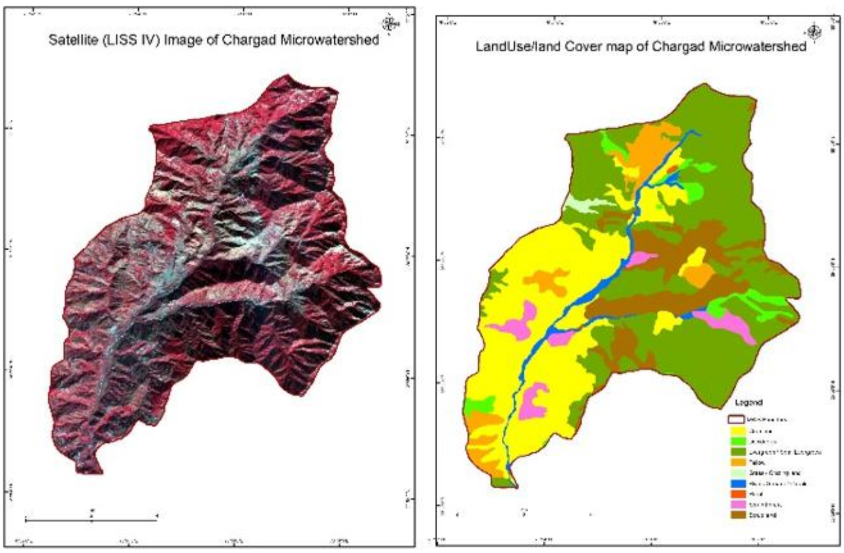

Figure 5: Satellite image and Landuse/ Land cover maps of charged MWS

The substantial proportion of fallow land (6.22%) is particularly noteworthy as a socio-ecological indicator. Fallow expansion in Himalayan agricultural landscapes is well-documented as a consequence of male out-migration, declining agricultural labour availability, and deteriorating economic viability of traditional hill farming (Chauhan, 2010).

Table 2: Land use/land cover classification of the Chargad Microwatershed (2021).

LULC Class	Area (%)	Management Implication
Evergreen/Semi-evergreen Forest	41.12	Maintain; spring-shed protection
Cropland	30.61	Sustainable intensification; agroforestry
Scrubland/Barren Land	11.75	Priority afforestation zone
Fallow Land	6.22	Assisted Natural Regeneration; horticulture
Scrub Forest (degraded)	3.65	Protection; enrichment planting
Deciduous Forest	3.25	Protection; regulated use
Grassland/Pasture	2.89	Rotational grazing; overseeding
Built-up/Settlement	0.55	Sanitation; waste management
Water Bodies/Streams	~0.96	Riparian buffer; bank protection
Total	**100.00**	—

Scrubland and barren land together constitute 11.75% of the watershed, representing significantly degraded terrain where both ecological function and agricultural productivity are severely diminished. These areas, characterized by sparse vegetation, compacted or eroded soils, and high runoff coefficients, constitute the highest priority zones for active restoration interventions.

Forest Density and Vegetation Health (NDVI Analysis): Forest type mapping based on the FSI classification (Champion & Seth) reveals that Ban Oak (Quercus incana) is the dominant forest type within the Chargad MWS, covering 21.02% of the total area, followed by Himalayan Chir Pine (Pinus roxburghii) at 15.41%, Western Mixed Coniferous Forest at 3.75%, and Moru Oak (Quercus dilatata) at 2.72%. These species assemblages are characteristic of mid-altitude zones (1,500–2,200 m) across the Garhwal Lesser Himalayas. Forest density assessment reveals that the broad canopy cover figures mask a severe degradation in forest quality: very dense forest (>70% canopy cover) constitutes merely 1.21% of the total watershed area, while moderately dense forest (40–70%) and open forest (10–40%) account for 28.87% and 11.67%, respectively (Table 4). Consequently, 58.25% of the nominal forest cover within the watershed is functionally open or degraded forest with limited hydrological and erosion-protection effectiveness.

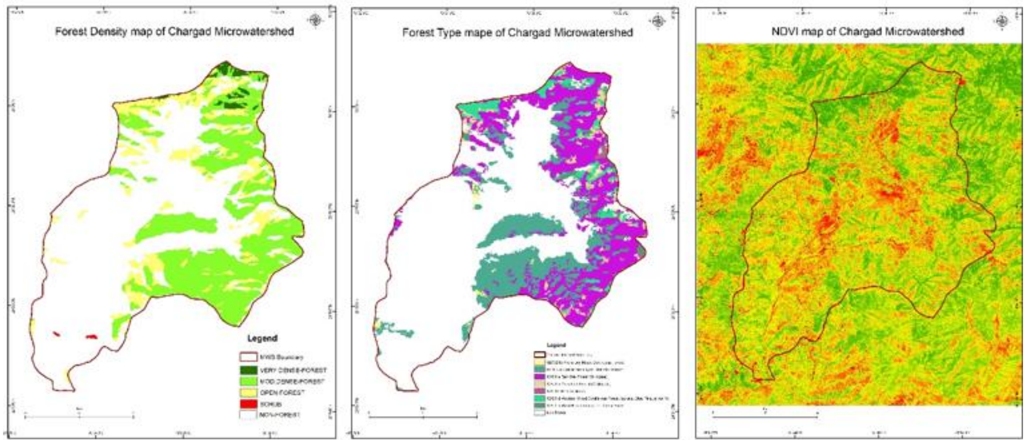

Figure 6: Forest density, Forest type and NDVI maps of charged MWS

NDVI analysis using satellite imagery quantitatively corroborates this degradation narrative. Moderate vegetation health (NDVI: 0.50–0.75) characterizes 59.08% of the watershed, representing vegetation under stress but not yet severely depleted. Poor vegetation health (NDVI: 0.25–0.50) covers 39.85%, a substantial proportion that includes degraded scrublands, over-grazed pastures, heavily extracted open forests, and fallow agricultural lands with sparse cover. However, healthy vegetation (NDVI: 0.75–1.00) is present over merely 0.55% of the watershed, indicating that functionally robust, high-productivity vegetation is extremely scarce. Barren and rocky surfaces account for 0.52% (Table 3). The Vegetation analysis highlights ecological strain in the watershed (Figure 6). The combination of moderate canopy cover and low NDVI in many areas suggests declining forest health, consistent with field reports of thinning stands.

Table 3: Forest density and NDVI vegetation health classification of the Chargad Microwatershed.

Category	Class / Range	Area (%)	Hydrological Significance
Forest Density (FSI)			
Very Dense Forest	> 70% canopy cover	1.21	High interception; recharge zone
Moderately Dense Forest	40–70% canopy cover	28.87	Moderate hydrological protection
Open Forest	10–40% canopy cover	11.67	Limited erosion protection
Non-forest	< 10% cover	58.25	High runoff; priority intervention
NDVI Vegetation Health			
Healthy Vegetation	NDVI 0.75–1.00	0.55	Maximum infiltration; minimal erosion
Moderate Health	NDVI 0.50–0.75	59.08	Moderate runoff generation
Poor Health	NDVI 0.25–0.50	39.85	High runoff; degradation risk
Barren/Rocky	NDVI 0.00–0.25	0.52	Maximum erosion risk; zero infiltration

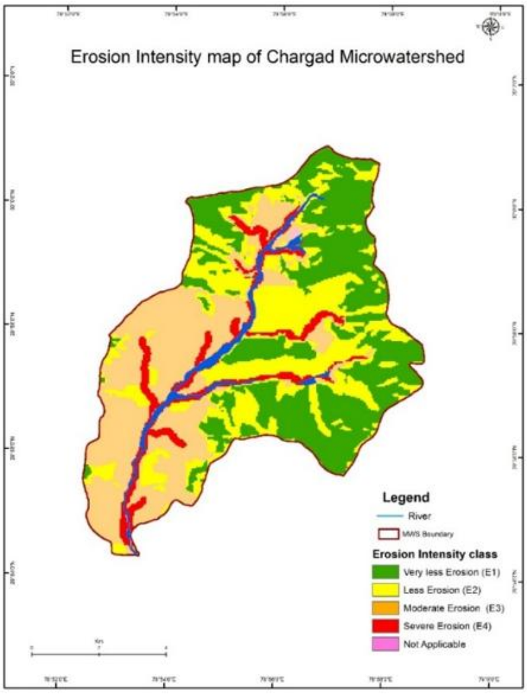

Figure 7: Forest density, Forest type and NDVI maps of charged MWS

Erosion Intensity Assessment: The composite erosion intensity assessment, integrating slope gradient, forest canopy density, and LULC classifications, reveals that a critical proportion of the Chargad MWS is under moderate to very high erosion risk (figure 7) Specifically, 30.93% of the total MWS area is classified under high erosion risk (E3) and 8.56% under very high erosion risk (E4), together constituting 39.49% of the MWS, approximately 551 ha within the critical erosion vulnerable category. Moderate erosion risk (E2) accounts for an additional 27.76%, leaving only 32.67% under low erosion risk (E1), with 0.083% classified as built-up (not applicable).

These findings (Table 4) are broadly consistent with erosion assessments from comparable Himalayan microwatershed studies. Mahapatra et al. (2018) documented widespread high-to-severe soil erosion in Uttarakhand's mid-hill districts using the USLE methodology.

Table 4: Erosion intensity classification of the Chargad Microwatershed (composite overlay method).

Erosion Risk Class	Code	Area (%)	Primary Landscape Units
Low	E1	32.67	Dense forest; well-vegetated north slopes
Moderate	E2	27.76	Open forest; stable agricultural terraces
High	E3	30.93	Degraded scrubland; steep slopes; terrace failure
Very High	E4	8.56	Gully margins; barren slopes; over-grazed pastures
Built-up (N/A)	—	0.083	Settlement areas
Total	—	**100.00**	—

Spring Water Source Assessment: Twenty-one distinct spring water sources were identified and geo-referenced within the Chargad Microwatershed, comprising 11 community-use sources (6 naulas and 5 dharas) across the five inhabited Gram Panchayats, and 10 perennial sources within Reserved Forest compartments of the Ameli (5) block (Table 5, Figure 8). Naulas represent the traditional stepped-stone spring enclosure while dharas are flowing spring outlets. These sources collectively constitute the primary water supply for all domestic, agricultural, and livestock needs of the MWS.

Measured peak discharge rates at community sources ranged from 1.05 LPM (Ghaghanidhar Naula) to 9.09 LPM (Pandhera tok Dhara). The lower-elevation sources in Salan and Dwila Talla (1,400–1,700 m) generally exhibited higher discharge rates than higher elevation naulas (>1,800 m) in Gadri GP, a pattern attributable to the greater accumulated catchment area and relatively better-preserved forest cover in the mid-elevation recharge zones of the lower GPs.

Multiple sources across the watershed were reported by community members to exhibit declining discharge over the past 10–15 years, with some naulas previously perennial now seasonal (drying between February and June). This observation is consistent with the broader crisis of declining spring discharge documented across the Indian Himalayan Region, attributed to the combined effects of deforestation of spring recharge zones, the shift from perennial to seasonal cropping on recharge-slope areas, and altered monsoon precipitation patterns (Chauhan, 2010). The 10 perennial sources identified within Reserved Forest compartments (Ameli 5, Compartments 1, 2, and 4) underscore the critical hydrological function of reserved forest land as the primary recharge zone for the watershed's spring network.

Table 5: Summary of spring water sources surveyed in the Chargad Microwatershed.

SN	GP	Village	Source Name	Type	Elevation (m)	Status/Remarks
1	Gadri	Gadri	Khancharyudhar	Dhara	1,850	Perennial; declining
2	Gadri	Gadri	Khandori	Naula	1,920	Perennial; stable
3	Gadri	Gadri	Pandhera Gad	Naula	1,750	Seasonal; dry May–Jun
4	Gadri	Gadri	Ghaghanidhar	Naula	1,979	1.05 LPM; declining
5	Gadri	Gadri	Bhanglwan	Naula	1,830	Perennial; stable
6	Gadri	Gadri	Sandana	Naula	1,780	Seasonal; declining
7	Dwila Talla	Dwila Talla	Pandhera tok	Dhara	1,620	Perennial; moderate flow
8	Salan	Salan	Pandhera tok	Dhara	1,438	9.09 LPM; stable
9	Chopda	Chopda	Koli Pani	Naula	1,550	Perennial; stable
10	Jhalpadi	Jhalpadi	Pandhera Pani	Naula	1,680	Seasonal; declining
11	Jhalpadi	Palidhar	Chandikharak	Naula	1,720	Perennial; stable
12–21	Reserve Forest	Ameli 5 Compart.1, 2, 4	Barma Pani, Lwitha Raul, Nauli, Nagad, etc.	Perennial	1,650–2,200	Perennial; critical recharge zone

Agricultural Potential Zones: The delineation of agricultural potential zones through GIS overlay of slope, LULC, soil depth and aspect layers identified approximately 514.1 ha (36.83% of total area) within the MWS. Spatially, these zones are concentrated along gentler valley-bottom terraces and mid slope terraced fields, particularly in the lower altitudinal zone.

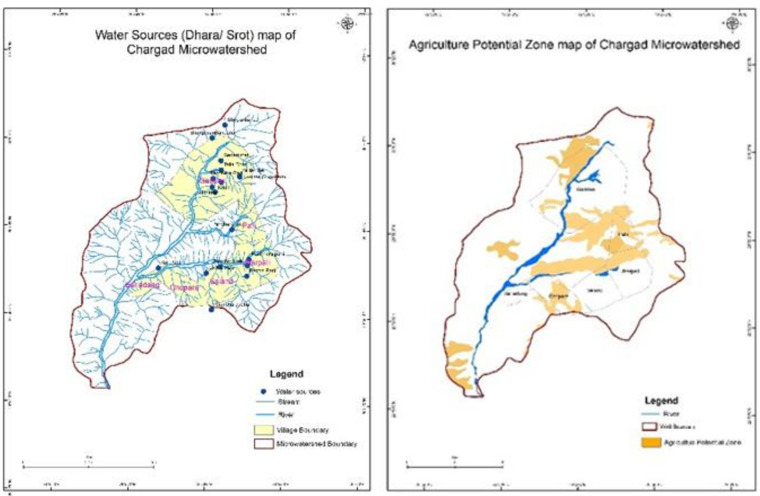

Figure 8: Water resource and agriculture potential maps of charged MWS

The GIS-delineated potential zones explicitly exclude steep slopes and forest land, concentrating recommended interventions on existing terraced fields and recoverable fallow lands where productivity enhancement is ecologically feasible and economically rational.

The fallow land reclamation is important where orchard development, agroforestry, or cover-crop-based systems can improve livelihoods, reduce erosion risk and enhance soil carbon (figure 6).

Socio-Economic Profile and Watershed Governance Challenges: The MWS supports a population of 4,390 persons across 778 households in five Gram Panchayats. Field surveys observed significant male out migration for urban employment, which has reduced agricultural labour availability and contributed to the fallow land expansion and declining maintenance of agricultural terraces and traditional irrigation canals. This observation aligns with the wider literature on demographic change and agricultural land abandonment in the Uttarakhand mid-hills (Chauhan, 2010). The Livestock populations across the MWS were a total of approximately 3,515 animals (cows, oxen, buffaloes, calves, sheep, and goats). This substantial livestock population exerts significant biotic pressure on common forest lands and degraded pastures. PRA consultations revealed widespread community awareness of declining spring discharges, increasing fuelwood scarcity, and reducing crop yields but also strong willingness to participate in spring rejuvenation, afforestation, and soil conservation activities if supported through an appropriate institutional and financing framework.

VI. Proposed Integrated Watershed Management Framework

Based on the integrated biophysical and socio-economic analysis, a spatially targeted, multi-pronged watershed management framework is proposed for the Chargad MWS (Figure 9), organized around five strategic pillars: structural soil and water conservation, vegetative restoration, springshed development, sustainable agricultural intensification, and community-based institutional strengthening. This framework aligns with national watershed programme guidelines (GOI, 2007) and is grounded in both PRA community consultations and geospatial evidence.

Structural Soil and Water Conservation Measures

- **Crate-Wire Stone Check Dams:** To be installed on second- and third-order streams in identified high-erosion (E3, E4) gully systems to reduce peak flow velocity, trap sediment, and promote in-situ groundwater recharge.
- **Brushwood/Stone Check Dams:** Low-cost vegetative check dams using locally sourced brushwood and stones are proposed for seasonal first-order streams in moderate-erosion zones as a cost-effective, community-constructible intervention for immediate sediment trapping.
- **Percolation Ponds and Dugout Ponds:** Percolation ponds are proposed at topographic depressions in upper- and mid-catchment zones to enhance groundwater recharge for spring rejuvenation. Dugout ponds for dry-season irrigation storage are recommended adjacent to identified agricultural potential zones in lower-altitude GP areas.
- **Crate-Wire Bank Spurs (Side Walls):** Along active bank-erosion segments of third- and fourth-order streams to arrest lateral channel migration and prevent further loss of productive riparian and agricultural land.
- **Village Ponds:** Multi-purpose water storage structures for livestock watering and groundwater recharge, recommended near habitation zones in each GP based on topographic suitability.

Vegetative Restoration Measures

- **Afforestation and Assisted Natural Regeneration (ANR):** Plantation of native species primarily Quercus *incana,* Quercus *leucotrichophora*, and Rhododendron *arboreum,* on identified scrubland and very-high-erosion (E4) zones, using community nurseries established in each GP. Priority afforestation zones are mapped in the western and southern portions of the MWS.
- **Pasture Development:** Improvement of degraded common grazing lands through overseeding with improved grass species (Chrysopogon *fulvus,* Cenchrus *ciliaris*) and introduction of rotational grazing management systems to reduce concentrated grazing pressure on degraded slopes.
- **Agroforestry Integration:** Promotion of multipurpose tree species (Grewia *optiva*, Celtis *australis,* Morus *alba*) within agricultural terraces to improve slope stability, provide biomass fodder that reduces forest dependence, and augment household income through non-timber forest product value chains.
- **Contour Trenching:** On moderate-slope (33–50% gradient) degraded forest and fallow patches to increase rainfall infiltration, reduce surface runoff velocity, and create favourable moisture conditions for vegetative recovery.

Springshed Development and Spring Rejuvenation: Decline in spring discharge at multiple naulas and dharas, spring-shed development is identified as the highest-priority livelihood-protection intervention in the Chargad MWS. Proposed measures include:

- Hydrogeological delineation of subsurface recharge zones contributing to each spring, using geological mapping and community-knowledge triangulation;
- Fencing and plantation of native tree species within identified spring recharge zones, protecting them from livestock grazing and agricultural encroachment;
- Construction of recharge pits, staggered contour trenches, and small percolation structures within spring recharge areas to maximize in-situ water percolation; and
- Protection and renovation of existing naula infrastructure (stone lining, covered catchment chambers) to reduce evaporation losses and contamination.

The 10 perennial sources within the Ameli (5) Reserved Forest compartments should be formally designated as protected springshed areas under forest department jurisdiction, with strict grazing and fuel-wood extraction exclusion.

Sustainable Agricultural Intensification: Within the identified agricultural potential zones, the following interventions are proposed:
- Promotion of climate-resilient crop varieties suited to mid-montane conditions, including improved millet, pulse, and off-season vegetable varieties with higher productivity and drought tolerance.
- Micro-irrigation systems (gravity-fed drip or sprinkler) linked to spring/naula sources to optimize water use efficiency during the dry season.
- Soil health improvement through balanced organic-inorganic nutrient management, promotion of green manuring, and compost production from livestock dung
- Terrace rehabilitation and maintenance also focus on the fallow land that represents the most readily recoverable agricultural resource within the watershed.

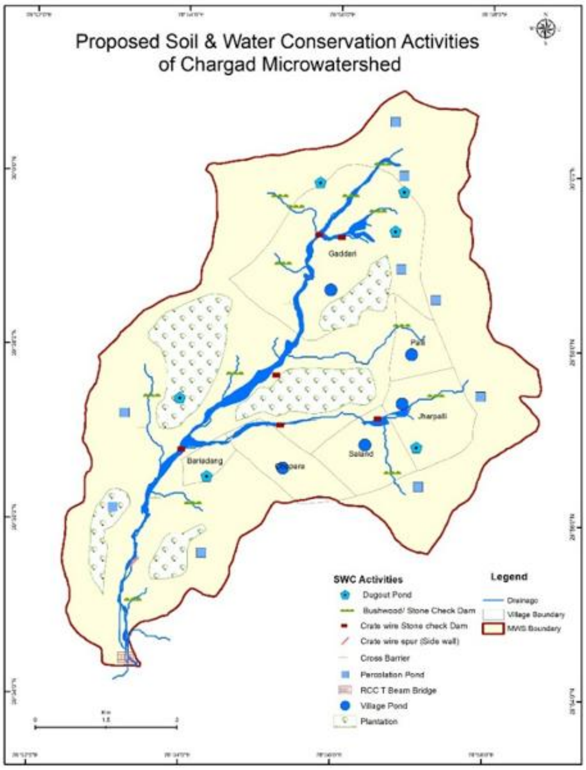

Figure 9: Proposed watershed activities maps of charged MWS

VII. Conclusions

This study presents the first comprehensive, RS-GIS and ground based integrated watershed assessment for the Chargad Microwatershed in Pauri Garhwal, Uttarakhand. Thematic data products collectively reveal a watershed under moderate-to-severe ecological stress that requires immediate, sustained, and spatially targeted conservation intervention. The integrated watershed management framework proposed for Chargad MWS, encompassing structural soil and water conservation works, native species afforestation, spring-shed protection, sustainable agricultural intensification, and community-based institutional strengthening, is explicitly grounded in geospatial evidence and PRA validated community priorities. Its implementation, prioritized through the spatially explicit erosion intensity and LULC maps generated by this study, offers a cost-effective and ecologically sound pathway toward watershed ecological restoration and improved rural livelihoods.

This study contributes a methodologically replicable template for integrated RS-GIS microwatershed assessment applicable to similar mid-Himalayan catchments across Uttarakhand and the broader Indian Himalayan Region. Future research should extend the biophysical characterization through quantitative soil erosion modeling, hydrogeological springshed delineation, multi-temporal LULC change analysis and a rigorous M&E framework to assess the ecological and socio-economic impact of proposed interventions over time. The integration of climate change projections into watershed management planning specifically the anticipated shifts in monsoon intensity, snowmelt timing, and drought frequency under representative concentration pathway (RCP) scenarios, represents a critical direction for enhancing the long-term resilience of management strategies for Himalayan microwatersheds.

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