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Contribution to Sustainable Development Goals through Geospatial Analysis of Groundwater Resources, Landslide Susceptibility, Land Use Dynamics and Tourism Sustainability in Shimla District

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ABSTRACT: Mountain ecosystems provide us ecological services, including freshwater resources, biodiversity conservation, climate regulation, and livelihood support. However, increasing urbanization, tourism expansion, land-use transformation, and climate variability have intensified environmental pressures across the Himalayan region. Although groundwater resources, landslide hazards, land use dynamics, and tourism sustainability have been widely investigated, these environmental components are commonly examined in isolation, limiting their usefulness for integrated planning and policy formulation. This study presents an integrated geospatial assessment framework that synthesizes previously completed investigations on groundwater potential mapping, landslide susceptibility assessment, multi-temporal land use and land cover (LULC) dynamics, future land-use prediction, and tourism sustainability for Shimla District, Himachal Pradesh, India. Rather than generating new thematic maps, the study integrates existing spatial evidence to examine the interactions among natural resources, environmental hazards, landscape transformation, and developmental pressures within a Sustainable Development Goals (SDGs) perspective.

The integrated analysis demonstrates that changes in land use influence groundwater recharge, urban expansion increases exposure to landslide hazards, and tourism development intensifies pressure on natural resources. Collectively, these interactions affect environmental resilience and the sustainability of mountain settlements. The proposed framework establishes explicit linkages between the study outcomes and Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). The study concludes by proposing an integrated geospatial decision-support framework to assist planners, resource managers, and policymakers in balancing environmental conservation with socio-economic development in mountain regions.

1. INTRODUCTION

Mountain ecosystems experience some of the most ecologically significant yet environmentally fragile landscapes on Earth. Occupying nearly one-quarter of the global terrestrial surface, mountains support diverse ecosystems, regulate regional and global climate, provide freshwater resources to downstream populations, and sustain the livelihoods of millions of people through agriculture, forestry, hydropower, and tourism. Despite their importance, mountain environments are increasingly subjected to multiple environmental pressures arising from rapid urbanization, infrastructure expansion, land-use transformation, tourism development, and climate variability (4). The cumulative effects of these stressors have accelerated ecological degradation and increased the vulnerability of mountain communities to natural hazards, thereby posing significant challenges to sustainable development (11,17).

The concept of sustainable mountain development has consequently received increasing attention within international environmental policy frameworks, particularly following the adoption of the United Nations Sustainable Development Goals (SDGs). Sustainable management of mountain resources requires balancing economic development with environmental conservation while maintaining ecosystem services that support both present and future generations.

Expansion of urban settlements, road construction, tourism infrastructure, deforestation, and changing agricultural practices have modified land-use patterns and disrupted ecological processes. Simultaneously, climate-induced changes in precipitation regimes and extreme weather events have increased the frequency and magnitude of hazards such as landslides, flash floods, and water scarcity. (1)

Among Himalayan regions, the state of Himachal Pradesh exemplifies these environmental challenges. The state has experienced rapid socio-economic development accompanied by significant transformations in land use and infrastructure. Tourism has become one of the principal contributors to regional economic growth, attracting millions of visitors annually. Shimla district, the capital district of Himachal Pradesh, provides a representative example of these interacting environmental processes. Characterized by rugged mountainous terrain, heterogeneous geology, dense forest cover, and rapidly expanding settlements, the district has experienced substantial environmental transformation over recent decades. Seasonal water shortages, recurrent landslides, forest fragmentation, and expansion of built-up areas have emerged as major environmental concerns (34).

Advances in Geographic Information Systems (GIS), Remote Sensing (RS), and spatial modelling have transformed environmental assessment by enabling integration of diverse geospatial datasets within a common analytical framework (5,6,13). Geographic Information Systems provide an effective platform for integrating these datasets and performing spatial analyses required for environmental planning. Among contemporary geospatial techniques, Multi-Criteria Decision Analysis (MCDA), particularly the Analytical Hierarchy Process (AHP) (20), has become widely accepted for evaluating environmental suitability and hazard susceptibility because it incorporates multiple conditioning factors within a transparent decision-making framework (9,15). Similarly, Cellular Automata–Markov (CA–Markov) modelling has emerged as an effective approach for simulating future land-use scenarios based on historical transition patterns. There is an increasing need for integrated geospatial frameworks capable of synthesizing multiple environmental dimensions within a common planning perspective (21).

The Sustainable Development Goals provide an appropriate framework for such integration because they recognize the interdependence of environmental conservation, resource management, disaster resilience, and socio-economic development (33). In mountain regions, groundwater management directly contributes to SDG 6 (Clean Water and Sanitation), hazard assessment strengthens SDG 11 (Sustainable Cities and Communities), land conservation supports SDG 15 (Life on Land), while adaptation to environmental change aligns with SDG 13 (Climate Action). Tourism sustainability further contributes to SDGs 8, 11, and 12 through promotion of sustainable economic development and responsible resource utilization.

The present study addresses this gap by developing an integrated geospatial assessment framework based on previously completed investigations of groundwater potential, landslide susceptibility, land use and land cover dynamics, future land-use prediction, and tourism sustainability within Shimla district.

The principal contribution of this study lies in demonstrating how diverse geospatial assessments can be combined to support sustainable mountain planning and policy development. Although the analysis is centred on Shimla district, the conceptual framework developed herein has potential applicability to other Himalayan regions experiencing comparable environmental and developmental challenges.

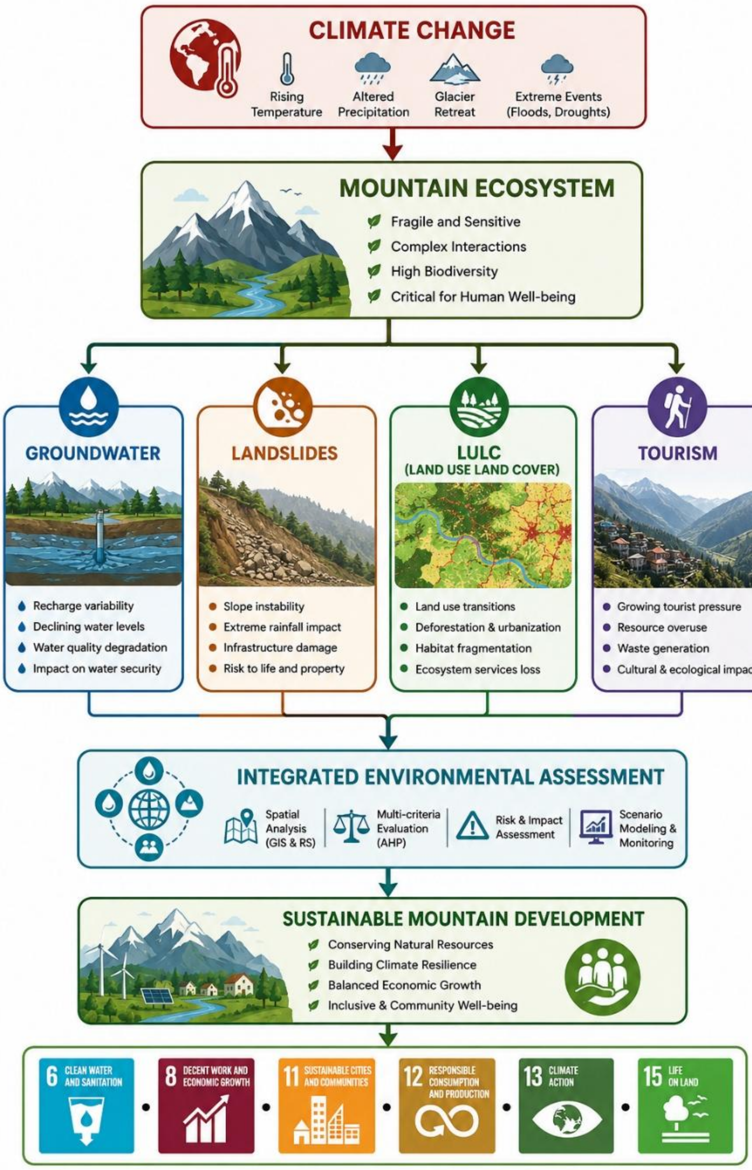

Figure 1: Conceptual framework illustrating the interrelationships among groundwater resources, landslide susceptibility, land-use dynamics, tourism sustainability, and Sustainable Development Goals

2. STUDY AREA

Shimla district is situated in the south-central part of Himachal Pradesh, India, within the ecologically sensitive Western Himalayan region (Figure 2). The district occupies a strategic geographical position between approximately 30°45' N and 31°44' N latitude and 77°00' E and 78°19' E longitude, encompassing an area of about 5,076 km². It shares administrative boundaries with the districts of Mandi and Kullu in the north, Kinnaur in the east, Solan and Sirmaur in the south, and Uttarakhand to the southeast. The district includes the state capital, Shimla city, which functions as the administrative, educational, and commercial centre of Himachal Pradesh.

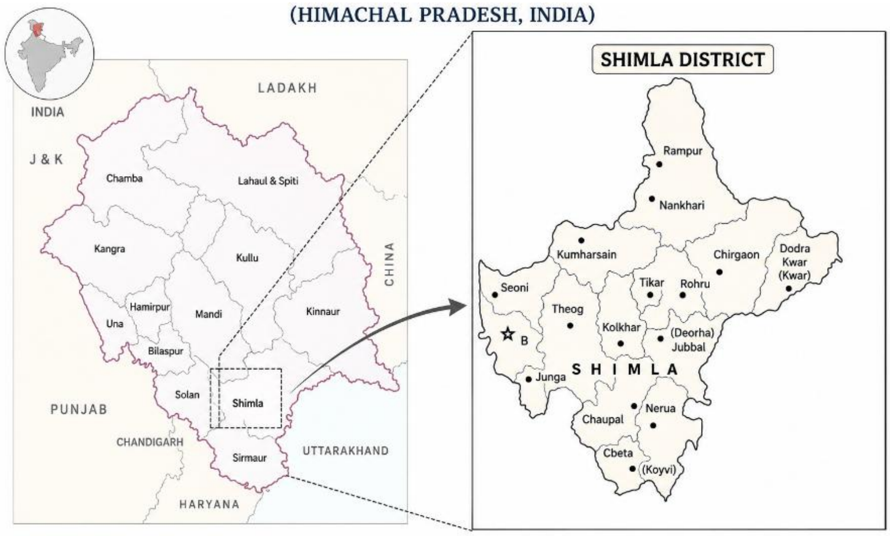

Figure 2: Geographical Location of Shimla District

The location of Shimla within the Himalayan mountain system exposes it to complex geomorphological, hydrological, and climatic processes. The General Characteristics are shown in Table 1. Consequently, the district provides an ideal natural laboratory for examining groundwater availability, landslide susceptibility, land-use dynamics, and tourism sustainability through integrated geospatial analysis. The physiography of Shimla district is characterized by highly rugged mountainous terrain, steep slopes, deeply incised valleys, and prominent ridge systems that have developed through active tectonic and geomorphological processes. Elevation varies from approximately 300 m to more than 6,000 m above mean sea level, resulting in pronounced variations in temperature, precipitation, vegetation, and land use across the district. Groundwater resources are generally confined to weathered and fractured geological formations, making recharge conditions highly dependent upon land use, slope, rainfall, and geological characteristics.

Table 1 General Characteristics of the Study Area

Parameter	Description
State	Himachal Pradesh
District	Shimla
Geographic Area	~5,131 km²
Latitude	30°45'–31°44' N
Longitude	77°00'–78°19' E
Elevation	~300–6,000+ m above mean sea level
Climate	Sub-tropical to alpine
Major Rivers	Sutlej, Giri, Pabbar
Dominant Land Uses	Forest, agriculture, horticulture, settlements
Principal Economic Activities	Tourism, horticulture, agriculture, forestry

The district comprises a variety of lithological formations, including quartzite, phyllite, schist, slate, limestone, and metamorphic rocks. Structural discontinuities, weathering, and tectonic deformation significantly influence groundwater occurrence and slope stability. The land-use pattern of Shimla district reflects the interaction between natural environmental conditions and human activities. During recent decades, increasing population, infrastructure development, and tourism have accelerated the expansion of built-up areas, particularly around Shimla city and major transportation corridors.

Shimla district represents one of the most environmentally sensitive mountain regions in the Western Himalaya, accordingly, Shimla district serves as an ideal case study for developing an integrated geospatial framework capable of supporting evidence-based planning, disaster risk reduction, environmental conservation, and sustainable mountain development.

3. MATERIALS AND METHODS

The present study adopts an integrated geospatial assessment framework that synthesizes the outcomes of four complementary investigations conducted in Shimla district: (i) groundwater potential zonation, (ii) landslide susceptibility assessment, (iii) land use and land cover (LULC) change analysis with future prediction, and (iv) tourism sustainability assessment. The methodological framework consists of four sequential stages: data acquisition, thematic geospatial analysis, integration of environmental components, and development of an SDG-oriented planning framework (10,14). Figure 3 presents the overall workflow adopted in the study.

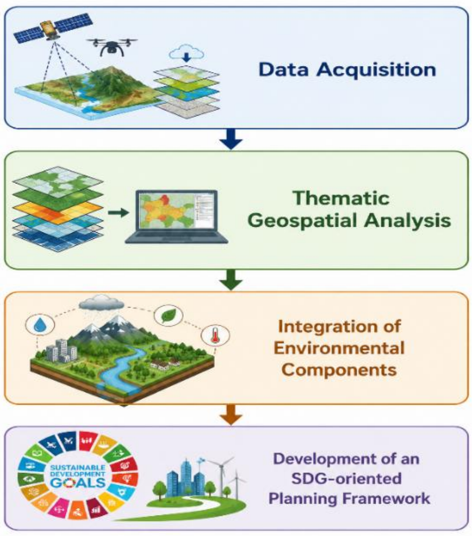

Figure 3: Methodology Framework

The study utilized a combination of remotely sensed imagery, digital terrain data, thematic maps, and secondary information obtained from authenticated national and international sources. Satellite imagery provided the basis for land use mapping (35), while terrain, geological, hydrological, and climatic datasets were employed for groundwater and landslide analyses. Tourism information was synthesized from government reports and published literature.

Table 2 Datasets Used in the Study

Dataset	Source	Resolution/Scale	Application
Sentinel-2 MSI	Copernicus Open Access Hub	10 m	LULC classification (2017, 2021, 2024)
SRTM DEM	ISRO Bhuvan / USGS	30 m	Elevation, slope, aspect, curvature
Rainfall Data	IMD / WorldClim	Gridded	Rainfall analysis
Drainage Network	Derived from DEM	Vector	Drainage density
Road Network	OpenStreetMap	Vector	Distance-to-road analysis
Administrative Boundary	Survey of India	Vector	Study area boundary

All spatial datasets were projected to a common coordinate reference system and processed within a Geographic Information System (GIS) environment to ensure spatial consistency (23). Raster datasets were resampled to compatible spatial resolutions, while vector datasets were converted into raster format where required for multi-criteria analysis. The resulting geodatabase

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served as the foundation for all thematic analyses conducted in the study. Terrain derivatives such as slope, aspect, and curvature were generated from the Digital Elevation Model using standard GIS spatial analysis tools.

3.1 Groundwater Potential Assessment

Groundwater potential mapping was performed using a GIS-based Multi-Criteria Decision Analysis (MCDA) framework incorporating the Analytical Hierarchy Process (AHP) (3,26). Seven thematic layers representing the principal hydrogeological controls on groundwater occurrence were considered in the analysis: Geology, Soil, Slope, Land Use/Land Cover, Rainfall, Aspect and Drainage Density. Each thematic layer was classified according to its relative influence on groundwater occurrence. Pairwise comparisons were undertaken to derive criterion weights following the Analytical Hierarchy Process, and the weighted thematic layers were integrated using weighted overlay analysis to produce the groundwater potential map (18,27). The final output classified the district into Very Low, Low, Moderate, High, and Very High groundwater potential zones (22,28). (Table 3)

Table 3 Groundwater Potential Delineation

Sr. No.	Different Potential Zones	Area (sq. km)	Percentage of Area (%)
1	Very Low	2.743	0.05
2	Low	625.043	12.31
3	Moderate	2396.712	47.22
4	High	1981.503	39.04
5	Very High	69.970	1.38

3.2 Landslide Susceptibility Assessment

Landslide susceptibility was evaluated using a GIS-based Multi-Criteria Decision Analysis approach integrated with AHP (2). Nine conditioning factors influencing slope instability were considered: Slope, Aspect, Elevation, Curvature, Geology, Rainfall, Drainage Density, Distance to Road and Land Use/Land Cover (25,36). Each thematic layer was reclassified according to its contribution to landslide occurrence.

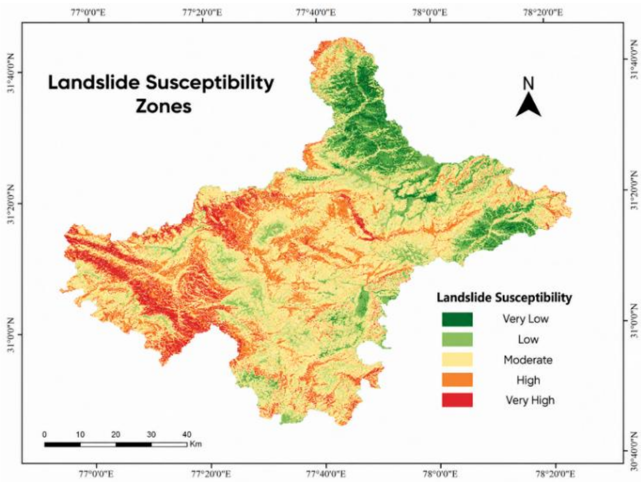

Figure 4: Zones of Landslide Susceptibility

Relative importance was assigned through pairwise comparison, and weighted overlay analysis was employed to generate the final susceptibility map (12). The results were classified into five susceptibility categories: Very Low, Low, Moderate, High, and Very High. The resulting susceptibility map (Figure 4) provides a spatial representation of hazard-prone areas and forms one of the principal environmental components integrated within the sustainable development framework.

3.3 Land Use and Land Cover Change Analysis

Multi-temporal land use and land cover maps were generated from Sentinel-2 imagery for the years 2017, 2021, and 2024 using supervised image classification. The classified maps were subsequently compared to quantify spatial and temporal changes in major land-use categories. Change detection analysis enabled identification of transitions among forest, agriculture, built-up areas, barren land, and water bodies, thereby providing insights into landscape transformation associated with urbanization and developmental activities. Future land use scenarios for 2030 and 2035 (Table 4) were simulated using the Cellular Automata–Markov (CA–Markov) model (7,8,24,37). Historical land-use transitions derived from classified imagery were used to generate transition probability matrices (36), which were subsequently combined with cellular neighbourhood rules to predict future landscape dynamics.

Table 4 LULC Predictions for 2030 and 2035

Land Use / Land Cover Category	Observed (2024) *(km²)*	Estimated (2030) *(km²)*	Estimated (2035) *(km²)*	Projected Land Cover Dynamics
Urban/Built-up Land	464.94	620.00	750.00	Rapid urban expansion expected
Forest and Tree Cover	2271.12	2183.00	2095.00	Progressive decline in vegetation cover
Grassland/Rangeland	2150.88	2113.00	2080.00	Gradual reduction over time
Exposed/Barren Land	132.37	125.00	119.00	Slow conversion to other land uses
Agricultural Land	40.35	25.00	25.00	Significant reduction followed by stabilization
Surface Water Bodies	5.51	4.00	3.00	Continuous shrinkage of water resources
Snow and Ice Cover	10.82	6.00	4.00	Increasing rate of snow and glacier loss

Rather than developing a separate spatial model, tourism was examined as a cross-cutting driver influencing land-use transformation, groundwater demand, infrastructure development, and environmental degradation. The assessment considered tourism-related pressures on natural resources, seasonal population fluctuations, expansion of built-up areas, and implications for long-term environmental sustainability.

3.4 Integration Framework for Sustainable Mountain Development

The principal methodological innovation of this study lies in the integration of the four thematic assessments within a unified environmental planning framework (38). Groundwater potential, landslide susceptibility, land use dynamics, future landscape scenarios, and tourism sustainability were synthesized to identify interactions among environmental resources, natural hazards, and developmental pressures.

Table 5 Integration of Research Components

Research Component	Method Applied	Primary Output	Contribution to Integrated Framework
Groundwater Potential	GIS–AHP	Groundwater Potential Zones	Water resource sustainability
Landslide Susceptibility	GIS–AHP	Hazard Zonation Map	Disaster risk reduction
LULC Analysis	Supervised Classification	LULC Maps (2017–2024)	Landscape dynamics
Future Prediction	CA–Markov	LULC Maps (2030 & 2035)	Scenario-based planning
Tourism Sustainability	Indicator-based synthesis	Environmental implications	Socio-economic integration

These integrated findings were subsequently interpreted within the context of the Sustainable Development Goals, enabling identification of policy priorities related to water resource management, disaster risk reduction, sustainable urban development, climate adaptation, ecosystem conservation, and responsible tourism. (Table 5)

4. RESULTS AND DISCUSSION

The integrated geospatial assessment of Shimla district provides valuable insights into the spatial interactions among groundwater availability, landslide susceptibility, land use dynamics, future landscape transformations, and sustainable tourism. By combining multi-source geospatial datasets, GIS-based spatial modelling, supervised image classification, and CA–Markov prediction, the study establishes a comprehensive environmental assessment framework for sustainable mountain planning. The results demonstrate that environmental processes in the Himalayan region are highly interconnected, where changes in one component directly influence the behaviour of others. The following subsections present the thematic findings and discuss their implications for sustainable resource management.

4.1 Groundwater Potential Assessment

Figure 5 illustrates the spatial distribution of groundwater potential zones generated through the integration of seven hydrogeological factors using the Analytical Hierarchy Process (AHP) and GIS-based weighted overlay analysis. The model classified the study area into five groundwater potential categories, namely Very Low, Low, Moderate, High, and Very High, representing the relative suitability of groundwater occurrence and recharge across Shimla district.

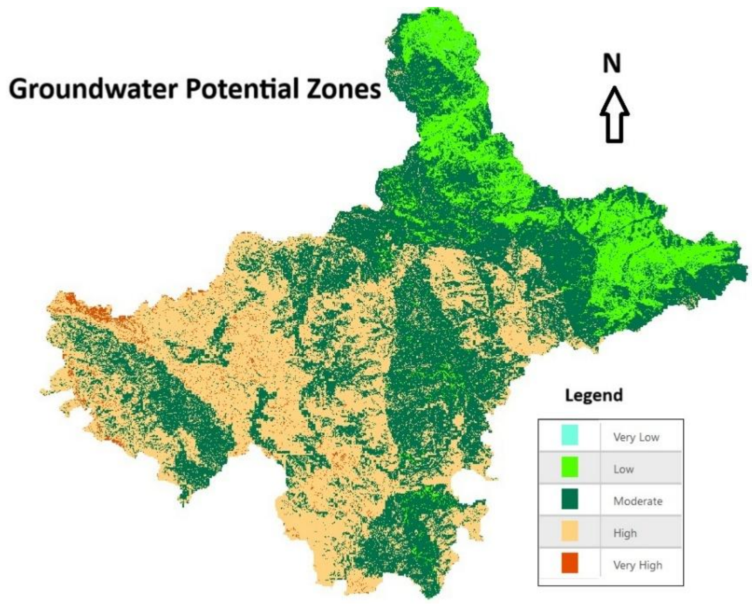

Figure 5: Spatial Distribution of Groundwater Potential Zones

The spatial analysis reveals considerable heterogeneity in groundwater availability owing to the complex mountainous terrain, varying lithological formations, differences in slope gradient, drainage characteristics, rainfall distribution, land use patterns, and lineament density. The groundwater potential map indicates that the Moderate groundwater potential zone constitutes the largest proportion of the district, covering approximately 2,397 km², representing nearly half of the geographical area (Figure 5). These areas are primarily distributed across the central portion of the district where moderate slopes, mixed forest cover, and favourable drainage characteristics collectively promote moderate infiltration and groundwater recharge. The High groundwater potential category, occupying approximately 1,981 km², is predominantly concentrated within the south-western and western parts of the district. The Very High groundwater potential zones occupy only about 70 km², representing approximately 1.38% of the total study area.

The observed groundwater distribution clearly reflects the strong influence of topographic and geological controls on groundwater occurrence in mountainous environments. From a resource management perspective, the groundwater potential map provides a valuable decision-support tool for identifying suitable locations for groundwater exploration, artificial recharge structures, spring rejuvenation programmes, rainwater harvesting interventions, and decentralized drinking water supply systems.

Overall, the groundwater assessment demonstrates that although Shimla district possesses substantial areas with moderate to high groundwater potential, these resources remain spatially unevenly distributed and highly sensitive to land use transformation and ongoing urban expansion. Consequently, integrated groundwater planning that combines hydrogeological suitability with future land use planning is essential for ensuring long-term water security within this environmentally fragile Himalayan landscape.

4.2 Landslide Susceptibility Assessment

Landslides are among the most significant geomorphological hazards affecting the Himalayan region, causing substantial damage to infrastructure, natural ecosystems, and human settlements. The GIS-based landslide susceptibility assessment undertaken in this study integrates nine thematic layers using the Analytical Hierarchy Process (AHP) and weighted overlay analysis to identify areas with varying levels of landslide susceptibility. The resulting susceptibility map classifies the district into five categories: Very Low, Low, Moderate, High, and Very High susceptibility, representing the relative probability of future landslide occurrence.

The spatial distribution of the susceptibility classes (Figure 4) demonstrates that landslide occurrence in Shimla district is highly heterogeneous and primarily governed by terrain characteristics and anthropogenic disturbances. The Moderate susceptibility zone occupies the largest proportion of the district, extending across much of the central and southern regions (29). These areas are characterized by moderate slopes, weathered rock formations, and mixed vegetation cover that provide relatively stable conditions under normal circumstances. However, intense monsoonal rainfall, localized excavation, or unplanned construction activities can significantly increase the likelihood of slope failures in these areas.

The High susceptibility zones are distributed mainly along steep mountain slopes, deeply incised valleys, road cuttings, and regions experiencing active developmental activities. These areas exhibit a combination of unfavourable geological and topographical conditions, including steep gradients, fractured lithology, shallow soil depth, and proximity to transportation corridors. The Very High susceptibility zones, although spatially limited, represent the most critical hazard areas within the district. These zones are generally concentrated along extremely steep slopes, structurally weak geological formations, and regions experiencing intensive weathering and erosion.

The susceptibility pattern observed in Figure 4 reflects the cumulative influence of the nine thematic parameters incorporated into the AHP model. Among these, slope emerged as one of the most influential factors controlling landslide occurrence. Steeper slopes increase gravitational stress acting on surface materials while simultaneously reducing soil cohesion and increasing runoff velocity. Geological formations also exert considerable influence on slope stability. Highly weathered and fractured rock masses possess lower shear strength and greater permeability, allowing rainwater infiltration that increases pore-water pressure and weakens slope materials. Rainfall acts as the primary triggering mechanism for landslides throughout Shimla district. During the southwest monsoon, prolonged and high-intensity rainfall infiltrates into weathered rock masses and soil profiles, increasing saturation levels and reducing effective stress. Areas with dense drainage networks experience continuous fluvial erosion at the toe of slopes, gradually reducing slope support and increasing instability. Similarly, valleys with deeply incised channels promote lateral erosion that further accelerates slope failures. Land use and land cover further influence slope stability through their effects on vegetation cover and surface hydrology. Dense forests contribute to slope stabilization by reinforcing soil through extensive root systems, reducing surface runoff, and enhancing infiltration.

An important observation emerging from the analysis is the inverse spatial relationship between groundwater potential and landslide susceptibility in several parts of the district. Areas exhibiting high groundwater recharge generally correspond to relatively gentle terrain where infiltration dominates over rapid runoff. In contrast, regions characterized by steep slopes and high landslide susceptibility often exhibit comparatively lower groundwater recharge because precipitation is rapidly converted into surface runoff before substantial infiltration can occur. Nevertheless, localized groundwater accumulation within fractured rock masses may increase pore-water pressure and trigger slope failures, particularly during prolonged rainfall events.

The landslide susceptibility map developed in this study has significant practical implications for disaster risk reduction, infrastructure planning, watershed management, and sustainable mountain development. Road alignments should be designed to minimize hill cutting wherever possible, while engineering stabilization measures such as retaining walls, rock bolting, bioengineering techniques, and effective surface drainage systems should be adopted in existing vulnerable locations. Furthermore, hazard zonation should be integrated into district-level land-use planning to discourage uncontrolled urban expansion into unstable terrain. Rainfall-based early warning systems, and continuous geospatial monitoring using remote sensing technologies should also be incorporated into disaster management strategies to reduce future landslide risk.

4.3 Land Use and Land Cover (LULC) Dynamics (2017–2024)

Land use and land cover (LULC) dynamics represent one of the most significant indicators of environmental transformation, reflecting the combined effects of natural processes and anthropogenic activities on landscape evolution. Monitoring these changes through remote sensing and Geographic Information Systems (GIS) provides an effective approach for evaluating landscape transformation and supporting sustainable land management strategies.

The supervised classification of Sentinel-2 imagery for the years 2017, 2021, and 2024 identified eight major LULC classes, namely Trees, Rangeland, Built-up Area, Crops, Bare Ground, Snow/Ice, Water Bodies, and Clouds. The temporal comparison reveals substantial changes in land cover composition during the seven-year study period, highlighting the increasing influence of urbanization and infrastructure development on the fragile Himalayan ecosystem.

The classification results indicate that forest and rangeland continue to dominate the landscape; however, both categories exhibit a gradual decline as built-up areas continue to expand (30). Simultaneously, agricultural land, water bodies, and snow-covered regions show varying degrees of reduction, suggesting increasing environmental pressures associated with climate variability and human activities.

Forest cover remained the dominant land cover class throughout the study period, accounting for 46.72% of the district area in 2017, 45.51% in 2021, and 44.74% in 2024. Although forests continue to occupy the largest proportion of the landscape, the continuous decline observed over the study period indicates progressive degradation of natural vegetation. The reduction of approximately 1.98 percentage points during seven years reflects the cumulative impacts of expanding settlements, transportation infrastructure, tourism-related development, and localized forest disturbances. Consequently, continued forest degradation is likely to reduce infiltration capacity, increase surface runoff, accelerate soil erosion, and enhance landslide susceptibility, particularly in steep mountainous terrain.

The most significant land cover transformation observed during the study period is the rapid expansion of built-up areas. Built-up land increased from 5.54% in 2017 to 7.48% in 2021, ultimately reaching 9.16% in 2024, representing an increase of approximately 65% over seven years. The expansion is primarily concentrated around Shimla city, suburban settlements, transportation corridors, and emerging peri-urban centres. Population growth, tourism development, institutional expansion, commercial infrastructure, and improved road connectivity have collectively accelerated urbanization across the district.

The increase in impervious surfaces significantly alters the hydrological response of the landscape by reducing infiltration capacity and increasing surface runoff. Consequently, urban expansion directly influences both groundwater recharge and landslide susceptibility. Impervious surfaces limit natural groundwater replenishment, while extensive hill cutting associated with urban development destabilizes slopes and increases erosion. The rapid urban growth observed during the study period therefore represents one of the most important drivers of environmental change within Shimla district and highlights the urgent need for sustainable urban planning practices that integrate hazard zonation, groundwater conservation, and ecosystem protection.

Snow and ice cover demonstrated considerable temporal variation, accounting for 0.52% in 2017, increasing substantially to 2.16% in 2021, and subsequently declining sharply to 0.21% in 2024. Such variations are influenced by differences in seasonal snow accumulation, acquisition dates of satellite imagery, and prevailing climatic conditions. Snow-covered areas play a vital role in regulating seasonal streamflow and groundwater recharge through gradual snowmelt. Therefore, long-term reductions in snow cover may significantly influence water availability within downstream catchments.

The most significant finding is the rapid increase in built-up area, which has expanded at the expense of forests, agricultural lands, and open landscapes. This transformation modifies the natural hydrological regime by increasing impervious surfaces, reducing groundwater recharge, accelerating runoff generation, and increasing erosion potential.

The observed land cover changes are also closely linked with the groundwater and landslide assessments as it has been observed in the study that areas experiencing rapid urban expansion generally correspond with reduced groundwater recharge potential owing to decreased infiltration capacity. Consequently, construction activities involving slope excavation and hill cutting increase the susceptibility of these regions to landslide disasters.

From an ecosystem and environment perspective, continued reduction of forest cover areas threatens biodiversity conservation, carbon sequestration, watershed stability, and ecosystem resilience. These changes collectively demonstrate that land use transformation acts as the central driver connecting hydrological processes, slope stability, environmental quality, and sustainable development within the Himalayan landscape. Overall, the LULC analysis highlights that Shimla district is undergoing continuous landscape modification driven primarily by urbanization and infrastructure development. The observed land cover changes emphasize the necessity of adopting integrated land-use planning strategies that balance developmental needs with environmental conservation. The classified maps generated in this study therefore provide an essential geospatial database for future environmental monitoring, hazard management, watershed conservation, and sustainable mountain planning.

In the study, the CA–Markov model was employed to simulate future land use and land cover (LULC) scenarios for 2030 and 2035 based on the observed transition patterns between 2017, 2021, and 2024. The model integrates Markov chain transition probabilities with Cellular Automata (CA) spatial allocation rules to predict the likely distribution of future land use classes. The prediction results indicate a continued transformation of the landscape, with built-up areas expected to increase significantly from 464.94 km² in 2024 to approximately 620 km² by 2030 and 750 km² by 2035, reflecting rapid urbanization and infrastructure development. In contrast, forest cover is projected to decline from 2,271.12 km² to 2,183 km² in 2030 and further to 2,095 km² in 2035, indicating continuous deforestation and fragmentation of natural vegetation. Similarly, rangelands are expected to decrease gradually from 2,150.88 km² in 2024 to 2,080 km² by 2035, while agricultural land is projected to reduce considerably and stabilize at around 25 km², highlighting increasing pressure on cultivable land. The model also predicts a gradual decline in **water bodies (5.51 km² to 3.00 km²)** and **snow/ice cover (10.82 km² to 4.00 km²)** by 2035, suggesting potential impacts of climate variability and changing land use on mountain hydrology.

Table 6 Predicted LULC Area Statistics for 2030 and 2035 using CA–Markov model

LULC Class	2024 (km²)	2030 (km²)	2035 (km²)	Trend
Built-up Area	464.94	620.00	750.00	Rapid Expansion
Trees	2271.12	2183.00	2095.00	Continuous Decline
Rangeland	2150.88	2113.00	2080.00	Moderate Decline
Bare Ground	132.37	125.00	119.00	Slight Decrease
Crops	40.35	25.00	25.00	Significant Reduction
Water	5.51	4.00	3.00	Gradual Decline
Snow/Ice	10.82	6.00	4.00	Rapid Decline

The projected trends suggest that, if current land use practices continue, Shimla district will experience accelerated urban expansion accompanied by reductions in forests, rangelands, agricultural land, and water resources. These changes are likely to increase pressure on groundwater resources, enhance landslide susceptibility, and reduce ecosystem resilience. Therefore, integrating predictive LULC modelling into regional planning can support sustainable land management and help formulate strategies for climate-resilient mountain development.

4.4 Tourism Sustainability

Tourism is one of the primary economic drivers of Shimla district, contributing significantly to regional employment, infrastructure development, and local livelihoods. However, the rapid growth of tourism has also intensified pressure on the region's fragile mountain ecosystem. Expansion of hotels, roads, commercial establishments, and residential infrastructure to accommodate increasing tourist inflow has accelerated land use transformation, altered natural drainage patterns, and increased the demand for natural resources. The geospatial analyses conducted in this study indicate that tourism-related development is closely associated with the observed increase in built-up areas and the gradual reduction in forest and rangeland cover between 2017 and 2024.

The increase in impervious surfaces resulting from urban and tourism infrastructure reduces groundwater recharge by limiting rainfall infiltration while simultaneously increasing surface runoff. Similarly, the expansion of tourism infrastructure along mountain slopes often requires hill cutting and road widening, which destabilize natural slopes and contribute to increased landslide susceptibility. Tourism also places considerable pressure on water resources through increased domestic consumption, hospitality services, and recreational activities. The projected decline in water bodies and groundwater recharge under future land use scenarios suggests that continued tourism growth without adequate resource management may lead to seasonal water shortages in Shimla and is already experienced each year.

Despite these challenges, tourism remains an essential component of Shimla's economy. Therefore, sustainable tourism strategies should focus on balancing economic development with environmental conservation. Promoting eco-tourism, regulating construction in environmentally sensitive areas, adopting rainwater harvesting systems, improving solid waste management, encouraging green building practices, and strengthening environmental impact assessment procedures can significantly reduce tourism-induced environmental degradation. Integrating tourism planning with geospatial monitoring provides an effective approach for ensuring that future tourism development remains environmentally sustainable while preserving the ecological integrity of the Himalayan landscape.

4.5 Integrated Environmental Assessment

The present study demonstrates that groundwater resources, landslide susceptibility, land use dynamics, and tourism development should not be considered as independent environmental components but rather as interconnected processes influencing the sustainability of mountain ecosystems. The integration of these four provides a comprehensive understanding of environmental change in Shimla district and represents the principal contribution of this research.

The temporal analysis of land use indicates continuous urban expansion accompanied by reductions in forest cover and rangelands. These transformations directly influence groundwater recharge by replacing permeable natural surfaces with impervious built-up areas, thereby reducing infiltration and increasing surface runoff. Reduced recharge subsequently affects groundwater availability, particularly in regions already characterized by moderate or low groundwater potential.

Simultaneously, rapid urbanization contributes to increased landslide susceptibility through extensive slope modification, hill cutting, road construction, and removal of stabilizing vegetation. It increases soil erosion, making slopes more vulnerable during intense rainfall events. Consequently, land use change acts as the common driver linking groundwater depletion and slope instability (32). The projected CA–Markov simulations indicate that these environmental pressures are likely to intensify in the coming decade. Continued expansion of built-up areas at the expense of forests and agricultural land is expected to reduce ecological resilience while increasing pressure on water resources and infrastructure. Such trends may amplify disaster risks, particularly under changing climatic conditions characterised by extreme rainfall events and declining snow cover.

Tourism further accelerates these interactions by increasing infrastructure demand, water consumption, and environmental disturbance. Therefore, sustainable mountain development requires an integrated planning framework (31) that simultaneously addresses land use planning, groundwater conservation, disaster risk reduction, ecosystem restoration, and sustainable tourism management (16).

The integrated assessment demonstrates that geospatial technologies provide an effective decision-support platform for evaluating complex environmental interactions. Table 7 shows major environmental interactions observed in this study and requires an integrated planning and policy framework to overcome the adverse situation. By combining GIS, remote sensing, AHP-based multi-criteria analysis, and predictive modelling, planners and policy makers can identify environmentally sensitive regions, prioritize conservation measures, and formulate evidence-based policies for sustainable mountain development.

Table 7 Major Environmental Interactions Identified in the Study

Environmental Component	Primary Change	Associated Impact
Urban Expansion	Increase in built-up area	Reduced groundwater recharge
Forest Decline	Vegetation loss	Increased runoff and slope instability

Hill Cutting	Infrastructure development	Increased landslide susceptibility
Tourism Growth	Increased resource demand	Water stress and ecological degradation
Climate Variability	Declining snow and water resources	Reduced long-term water availability

4.6 SDG Linkages and Policy Implications

The findings of this study contribute directly to several United Nations Sustainable Development Goals (SDGs) by providing a geospatial framework for sustainable mountain resource management. (Figure 6). The integrated assessment highlights the importance of combining environmental monitoring with evidence-based planning to achieve long-term ecological and socio-economic sustainability.

The groundwater potential assessment supports SDG 6 (Clean Water and Sanitation) and SDG 15 (Life on Land) by identifying suitable zones for groundwater exploration, artificial recharge, rainwater harvesting, and watershed management. Protecting high groundwater potential areas can improve water security for both rural communities and rapidly growing urban centres. The landslide susceptibility assessment contributes to SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) by identifying hazard-prone areas where infrastructure development should be carefully regulated. Incorporating susceptibility maps into land use planning can significantly reduce disaster risks and improve the resilience of mountain settlements. The analysis of land use change and future LULC prediction align with SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action) and SDG 15 (Life on Land) by demonstrating the impacts of urban expansion on forest ecosystems, water resources, and landscape stability. Conservation of forests, restoration of degraded land, and sustainable land management practices are essential for maintaining ecosystem resilience under changing climatic conditions. The tourism sustainability assessment supports SDG 8 (Decent Work and Economic Growth) by emphasizing environmentally responsible tourism development that generates economic benefits while minimizing ecological degradation. Promoting eco-tourism, green infrastructure, and sustainable resource utilization can enhance long-term economic growth without compromising environmental quality.

Collectively, the integrated findings also contribute to SDG 12 (Responsible Consumption and Production) by encouraging efficient land and water resource management, sustainable infrastructure development, and environmentally responsible planning practices. Also Table 8 shows linkage of research outcomes with sustainable development goals and suggested actions that can be implemented.

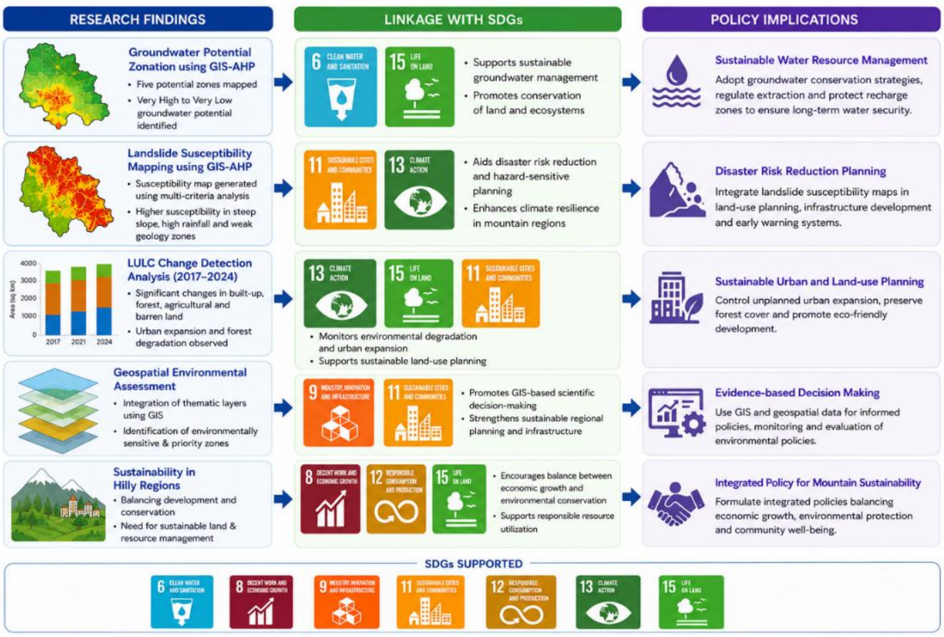

Figure 6: Contribution to Sustainable Development Goals and Policy Implications

Table 8 Linkage of Research Outcomes with Sustainable Development Goals

SDG	Research Contribution	Suggested Action
SDG 6 Clean Water and Sanitation	Groundwater potential mapping	Artificial recharge, spring rejuvenation, rainwater harvesting
SDG 8 Decent Work and Economic Growth	Sustainable tourism assessment	Eco-tourism, green infrastructure, carrying capacity assessment
SDG 11 Sustainable Cities and Communities	Landslide susceptibility mapping	Hazard-based land use zoning and resilient infrastructure planning
SDG 12 Responsible Consumption and Production	Efficient land and resource management	Sustainable construction and resource conservation
SDG 13 Climate Action	Future LULC prediction and environmental monitoring	Climate-resilient planning and adaptation strategies
SDG 15 Life on Land	Forest conservation and landscape assessment	Afforestation, ecosystem restoration, biodiversity conservation

The study demonstrates that sustainable management of Himalayan Mountain environments requires integrated planning rather than isolated sectoral interventions. Based on the findings, the following policy recommendations are proposed:

- Integrate groundwater potential and landslide susceptibility maps into district-level land use planning and regional planning.
- Restrict construction and large-scale infrastructure projects in High and Very High landslide susceptibility zones.
- Promote rainwater harvesting, artificial groundwater recharge, and spring rejuvenation programmes in moderate to high groundwater potential areas.
- Strengthen forest conservation, afforestation, and watershed restoration to improve groundwater recharge and slope stability.
- Encourage eco-tourism, green building practices, and sustainable infrastructure development to minimize environmental impacts.
- Establish a GIS-based environmental monitoring and decision-support system for continuous assessment of land use changes, hazard risks, and resource availability.
- Incorporate predictive LULC modelling into regional development plans to proactively manage future urban growth and environmental challenges.

Overall, the integration of geospatial technologies with sustainable development planning provides a scientifically robust framework for achieving balanced socio-economic growth while conserving the ecological integrity of Shimla district. The findings of this study offer valuable guidance for policymakers, planners, and environmental managers working towards resilient and sustainable mountain development.

5. CONCLUSIONS

The present study developed an integrated geospatial framework to assess the environmental dynamics of Shimla district, Himachal Pradesh, by combining groundwater potential zone mapping, landslide susceptibility zone mapping, land use and land cover (LULC) change dynamics, future landscape prediction using the Cellular Automata–Markov (CA–Markov) model, and tourism sustainability within a single decision-support framework and policy implications. Unlike conventional studies that evaluate these environmental components independently, the present research demonstrates that sustainable mountain development requires a holistic understanding of the interrelationships among natural resources, environmental hazards, landscape transformation, and anthropogenic pressures. The thematic assessments in GIS software provides a comprehensive basis for sustainable planning in the ecologically fragile Himalayan region (19).

The groundwater potential zone assessment revealed that groundwater availability in Shimla district is highly influenced by geological formations, slope, drainage density, rainfall, lineament density, and land use characteristics. While a significant proportion of the district falls within moderate to high groundwater potential classes, the spatial distribution remains uneven because of complex terrain and hydrogeological variability. These findings highlight the importance of protecting favourable recharge zones through watershed management, rainwater harvesting, and artificial recharge programmes to ensure long-term water security.

The landslide susceptibility analysis demonstrated that steep slopes, weak lithological formations, high rainfall intensity, proximity to roads, and increasing anthropogenic interventions are the major factors governing slope instability. The identification of high and very high susceptibility zones provides valuable information for hazard-sensitive land use planning, infrastructure development, and disaster risk reduction. Integrating susceptibility maps into regional planning can substantially reduce risks associated with unplanned construction and expanding transportation networks in mountainous terrain.

The multi-temporal LULC analysis highlighted significant landscape transformation between 2017 and 2024, characterized by continuous expansion of built-up areas and gradual reduction in forest cover, rangelands, agricultural land, and water resources. The CA–Markov simulation further indicated that these trends are likely to continue through 2035 if current development patterns remain unchanged. The projected increase in urbanized areas, accompanied by declining forests and water resources, underscores the urgent need for sustainable land use policies that balance developmental requirements with environmental conservation. These findings demonstrate the value of predictive geospatial modelling in supporting proactive planning and long-term resource management.

The tourism sustainability emphasized that although tourism contributes substantially to the regional economy, unmanaged tourism expansion has intensified environmental pressures through increased water demand, land transformation, infrastructure development, waste generation, and ecological disturbance. The study demonstrates that tourism planning should be integrated with groundwater conservation, hazard assessment, and environmental monitoring to ensure that economic development does not compromise ecosystem integrity.

The principal scientific contribution of this research lies in the integration of groundwater potential assessment, landslide susceptibility mapping, LULC dynamics, future landscape prediction, and tourism sustainability within a unified GIS-based environmental planning framework. This approach moves beyond traditional single-theme studies by explicitly demonstrating the interactions among hydrological processes, slope stability, land use transformation, and socio-economic development. The proposed framework therefore provides a valuable decision-support tool for planners, environmental managers, and policymakers engaged in sustainable mountain development.

The study also demonstrates the significant potential of Geographic Information Systems (GIS) and Remote Sensing as effective tools for environmental monitoring and spatial decision-making. The integration of satellite imagery, terrain analysis, multi-criteria decision analysis (AHP), and predictive modelling enables efficient assessment of complex environmental systems over large spatial extents while supporting evidence-based planning (40). Such geospatial technologies are increasingly important for monitoring Sustainable Development Goal (SDG) indicators, evaluating environmental change, and developing climate-resilient development strategies.

From a policy perspective, the findings recommend incorporating groundwater potential maps and landslide susceptibility maps into district-level land use planning, restricting development within environmentally sensitive and hazard-prone areas, promoting afforestation and watershed restoration, strengthening groundwater recharge programmes, regulating tourism infrastructure based on carrying capacity assessments, and establishing GIS-based environmental monitoring systems for continuous landscape assessment. These measures will contribute to improving ecological resilience while supporting sustainable socio-economic development within the Himalayan region.

5.1 Contribution towards Sustainable Development Goals (SDGs)

Beyond its scientific contributions, the present study provides a practical framework for advancing several United Nations Sustainable Development Goals (SDGs) through integrated geospatial assessment and evidence-based environmental planning. The groundwater potential assessment contributes directly to SDG 6 (Clean Water and Sanitation) and SDG 15 (Life on Land) by identifying suitable zones for groundwater exploration, recharge enhancement, and sustainable water resource management. The landslide susceptibility assessment supports SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) by facilitating hazard-informed land use planning, resilient infrastructure development, and disaster risk reduction in mountainous regions. The analysis of land use and land cover dynamics, together with future landscape prediction, contributes to SDG 13 (Climate Action) by providing a scientific basis for climate adaptation strategies and long-term environmental monitoring, while also supporting SDG 15 (Life on Land) and SDG 11 (Sustainable Cities and Communities) through the identification of forest degradation, ecosystem fragmentation, and priority areas for ecological restoration. Furthermore, the tourism sustainability assessment aligns with SDG 8 (Decent Work and Economic Growth) by promoting environmentally responsible tourism that balances economic benefits with conservation objectives, and SDG 12 (Responsible Consumption and Production) through recommendations for sustainable resource utilization and environmentally conscious infrastructure development. Collectively, the integrated geospatial framework developed in this study demonstrates how spatial technologies can support multiple SDGs simultaneously by enabling informed decision-making, enhancing environmental resilience, and promoting sustainable mountain development.

5.2 Policy Recommendations and Practical Applications

The integrated environmental assessment developed in this research offers a comprehensive decision-support framework that can be effectively utilized by government agencies, urban planners, disaster management authorities, environmental managers, and policymakers. The generated groundwater potential and landslide susceptibility maps can be incorporated into district and state-level spatial planning to guide groundwater extraction, spring rejuvenation programmes, infrastructure siting, and hazard-sensitive land use zoning. The LULC change analysis and CA–Markov predictions provide valuable information for preparing regional development plans, regulating urban expansion, conserving forests, and protecting environmentally sensitive areas from unsustainable development. The findings can further support watershed management programmes, climate adaptation planning, biodiversity conservation initiatives, eco-tourism planning, and integrated catchment management across the Himalayan region. At the institutional level, the proposed framework may be adopted by agencies such as the Department of Town and Country Planning, State Disaster Management Authorities (SDMA), Forest Departments, Jal Shakti Department, and local municipalities for developing GIS-based environmental monitoring systems and evidence-based policy interventions. Moreover, the methodology is transferable to other mountainous regions of India and similar fragile ecosystems worldwide, providing a standardized approach for integrating hydrogeological assessment, hazard mapping, landscape monitoring, predictive modelling, and sustainability planning. The implementation of such integrated geospatial decision-support systems will strengthen policy formulation, improve climate resilience, enhance natural resource governance, and facilitate the achievement of long-term sustainable development objectives.

5.3 Limitations and Future Scope

Despite its comprehensive approach, the present study has certain limitations. The analyses primarily rely on available satellite imagery, secondary spatial datasets, and deterministic multi-criteria decision-making techniques. Future investigations could incorporate higher-resolution satellite data, LiDAR-derived terrain information, continuous groundwater observations, and long-term landslide inventories to improve spatial accuracy. Furthermore, socio-economic variables such as population growth, infrastructure investment, land ownership patterns, and community vulnerability were not explicitly integrated into the modelling framework. Their inclusion would provide a more comprehensive understanding of mountain sustainability.

Future research should also explore the integration of climate change projections with land use prediction to evaluate the cumulative impacts of changing precipitation regimes and temperature on groundwater recharge, landslide occurrence, and ecosystem resilience. Advanced machine learning algorithms such as Random Forest, Extreme Gradient Boosting (XGBoost), Support Vector Machine (SVM), Artificial Neural Networks (ANN), and Deep Learning models may further improve the predictive capability of groundwater and landslide susceptibility assessments. In addition, coupling geospatial modelling with ecosystem service valuation, socio-economic indicators, and climate adaptation scenarios would support the development of comprehensive mountain sustainability frameworks applicable to other Himalayan regions and mountainous environments worldwide.

In conclusion, the geospatial framework developed in this study demonstrates that sustainable mountain development depends upon coordinated management of water resources, land use, hazard mitigation, ecosystem conservation, and tourism planning (39). By combining multiple environmental assessments within a single GIS-based analytical framework, the study provides a scientifically robust and practically applicable approach for supporting evidence-based planning, enhancing environmental resilience, and contributing to the achievement of the Sustainable Development Goals in fragile mountain ecosystems.

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