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Environmental vulnerability assessment of eco-development zone of Great Himalayan National Park, Himachal Pradesh, India

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ABSTRACT

The Great Himalayan National Park (GHNP), located in western Himalaya, is a key mountainous ecosystem prone to environmental vulnerability because of anthropogenic stress and the natural disasters, viz., landslide and forest fire. We assessed the environmental vulnerability of the eco-development zone of GHNP using remote sensing (RS) and geographic information system (GIS) technologies. To quantify the environmental vulnerability, a numerical model using spatial principal component analysis (SPCA) was developed. This model considered five factors: land use/land cover, forest canopy density, forest fire risk, landslide susceptibility and human population density. The environmental vulnerability integrated index (EVSI) calculated for the 1990, 2000 and 2010 periods was found to be 2.00, 2.72, and 3.40, respectively. The results showed temporal increase in the environmental vulnerability in the zone. Based on the numerical outputs, the vulnerability of the region was categorized into five classes: potential, slight, medium, high, and severe. The primary factor responsible for the increase in vulnerability overtime was land use/land cover change in the study area due to hydro-electric power projects, construction of roads, and other infrastructure developments. Forest fire and decreased forest canopy density are other major contributing factors responsible for the increase in the environmental vulnerability. Our results indicated that integration of RS, GIS and SPCA can effectively quantify and assess environmental vulnerability.

1. Introduction

Environment, development, and sustainability are the three most significant issues of concern worldwide. Due to increasing demand on resources, the environment of earth is in danger. Pressure on the environment is increasing due to exponential population growth and development. Protected areas are increasingly seen to be crucial for biodiversity conservation and ecosystem services. Anthropogenic activities are degrading and depleting the protected areas. The Himalaya is one of the most ecologically fragile and economically under-developed parts of the world (Tiwari, 2000). The ecosystems in Himalaya are highly stressed due to ever-increasing human and cattle populations and consequent pressure on land. Great Himalayan National Park (GHNP) is one of the most important conservation areas in India. The people in and around GHNP are traditionally dependant on GHNP resources for the livelihood. The economy of these people depends on agriculture, livestock, and minor forest products (Nagia and Kumar, 2001). The forests and grasslands around the human settlements are degraded due to overuse. Further, the developmental activities like construction of hydro-electric power projects and transport network have a devastating impact. Once the ecosystem is degraded, recovery takes a long time.

Environmental vulnerability is related to the risk of damage to the natural environment. The entities at risk include ecosystem, population, and the physical and biological processes and these are affected by anthropogenic activities (Kaly et al., 2002). The concept of vulnerability can be precisely expressed in terms of the exposure, sensitivity and the adaptive capacity of the system. The environmental vulnerability assessment is used for the comprehensive evaluation of the resource system affected by natural conditions and intervened by human activities (Fan et al., 2009).

The issue of environmental vulnerability to external and internal stress factors has been a subject of active research. Several methods have been developed to analyze the vulnerability. Mathematical modelling (Wilson et al., 2005), analytical hierarchy process (Wang et al., 2008), fuzzy evaluation method (Enea and Salemi, 2001), artificial neural network (Dzeroski, 2001), comprehensive evaluation method (Goda and Mastuoka, 1986), grey evaluation method (Hao and Zhou, 2002), and spatial multi-criteria

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evaluation (SMCE) (Enete et al., 2010) have been used for quantitative environmental vulnerability assessment. Environmental vulnerability analysis is innately multi-dimensional, and it is necessary to determine the interrelationship of all the factors of vulnerability in order to assess overall environmental vulnerability. Principal Component Analysis (PCA) or factor analysis is a robust statistical analysis technique to reduce the dimensionality of data and extract the innate relationship by developing composite variables. However, PCA is not linked spatially. On the other hand, GIS is able to map several variables and their distributions, but it is difficult to find relationship among different factors using GIS. The integration of GIS and PCA, hereafter referred as spatial principal component analysis (SPCA), can provide an insight into the spatial tendencies of the factors. SPCA have been applied in a wide array of environmental studies for revealing the relationships among different indicators (Calais et al., 1996; Yu et al., 1998). Shi et al. (2009) used spatial SPCA to determine effects of land use change on environment quality. Li et al. (2006a,b) found SPCA to be useful method for environmental vulnerability assessment. Using this method, an environmental vulnerability index can be calculated based on the coefficients of linear correlation and the contribution of factors can also be assessed (Parinet et al., 2004). Due to this merit, the SPCA was used for environmental vulnerability assessment in this study.

The study aimed at assessment of the environmental vulnerability of eco-development zone of GHNP, Kullu, Himachal Pradesh in Indian Himalaya over three time periods – 1990, 2000 and 2010, to analyze the environmental vulnerability over time and suggest remedial measures to overcome the problem. The study addresses the research questions, viz., what is the spatial distribution and changing pattern of environmental vulnerability and what are the alternative measures available for decreasing the environmental vulnerability in the study area.

2. Materials and methods

2.1. Study area

The eco-development zone of GHNP falls in the Kullu district of Himachal Pradesh, India (31°30′–31°55′ N and 77°20′–77°35′ E), and lies in west of GHNP, covering an area of 264 km^2 (Fig. 1). The eco-development zone is an important unit of GHNP and acts as a buffer zone between core zone and the unprotected area. The climate of the study area is typical of western Himalayan ranges; it varies from temperate to alpine with four prominent seasons, viz., winter (October to mid-March), spring (mid-March to mid-April), summer (mid-April to June) and rainy season (July to September). Rains are confined to monsoon season with snowfall during winters. The area receives 1000–2000 mm rainfall during southwest monsoon (Gaston et al., 1981).

The western Himalaya is considered an endemic bird area by Birdlife International, supporting many restricted-range species, as well as an international conservation hotspot (Bibby et al., 1992). This region is also home for many threatened and endangered plant and animal species. The study area is a part of one of the two National Parks in the world that support populations of endangered western tragopan (*Tragopan melanocephhalus*) and is habitat for a large number of rare species (Gaston and Garson, 1992). In June 2014, the GHNP was added to the UNESCO list of World Heritage Sites (http://whc.unesco.org/en/news/1160). It is also part of ‘Himalaya’ biodiversity hotspot.

The GHNP is well known for its rich biodiversity. The vegetation comprises of: Alpine scrub, Alpine meadows, Temperate broadleaved forest, Temperate conifer forest, Temperate broadleaved conifer mixed forest, Sub-alpine forest, Temperate grasslands (Champion and Seth, 1968). Additionally, the area provides shelter to various faunal species and many scheduled and endangered species (Vinod et al., 1997; Ramesh et al., 1998; Uniyal and Mathur, 1998). The biological richness of the study area makes it one of the most important conservation sites in the world.

There are numerous settlements in and around the GHNP. About 102 small villages are located in the eco-development zone (Nagia et al., 1999). Tucker (1997) studied the social structure of the study area in detail and concluded that the villagers are key to preserving the biodiversity since their use of natural resources and their response largely determine the human impact. Use of forest and its products is important dimension of villagers' subsistence. They have traditional right to use forest for livestock grazing and firewood collection; apart from this they collect a variety of medicinal herbs and wild mushrooms seasonally (Pandey and Wells, 1997; Nagia et al., 1999). Since their culture, religion, and polity have evolved locally, people are deeply attached with the environment.

The environmental degradation, due to the ever-increasing impacts of the rapidly increasing population and development activities, poses great menace to ecosystem and biodiversity of GHNP. Lack of active participation of local people is another hurdle in the efficient implementation of conservation efforts. The conflict between conservation and livelihood has become an integral part of all conservation planning in GHNP (Saberwal and Chhatre, 2003). The GHNP management has been engaged in much needed conservation activities in the Park since it Park was established in 1984 while Government wants to utilize the water resources for generation of electricity in and around the GHNP. Through a peculiar sequence of events in 1999, a patch of 10 km^2 of the Park area was carved out to make way for the Parvati hydro-electric power station (Saberwal and Chhatre, 2003). This dichotomy made the conservation efforts difficult and rendered the environment highly vulnerable. No vulnerability assessment has been conducted in the study area so far.

2.2. Materials and methods

The medium resolution Landsat TM ortho-rectified imagery of 27 March 1990, 29 March 2000, and 25 March 2010 were downloaded from Global Land Cover Facility (GLCF) web site (http://glcf.umiacs.umd.edu/) and used in the present study (Fig. 2). Two data sets, viz., remote sensing data and human population census data were used in the study. From these data sets, the factors defining environmental vulnerability were assessed. The factors used for vulnerability assessment were – land use/land cover (LULC), forest canopy density, forest fire risk, population density, and landslide susceptibility. Initially, the LULC and forest canopy density maps were prepared and modified after field work. Later forest fire risk zonation map, landslide susceptibility map and the population density map were prepared. All the factor maps were integrated by means of spatial principal component to compute the environmental vulnerability index. From environmental vulnerability index of three time periods, vulnerability maps were generated and change trend was analyzed.

The study area was extracted from all the images using GHNP boundary. The LULC mapping of the recent time period was done using on-screen visual interpretation technique. A field visit was made to correlate the image tonal variations with the ground features. Trimble Juno SD GPS receiver was used during field work. All the features on the image were identified and delineated. The recent time period vector layer was used to map the LULC of 1990 and 2000 with necessary modifications. The classification accuracy of the LULC map of 2010 was assessed using a different set of field points.

Forest canopy density map for all the three time periods were prepared by using on-screen visual interpretation. The LULC map was used to delineate forest canopy density. The forest

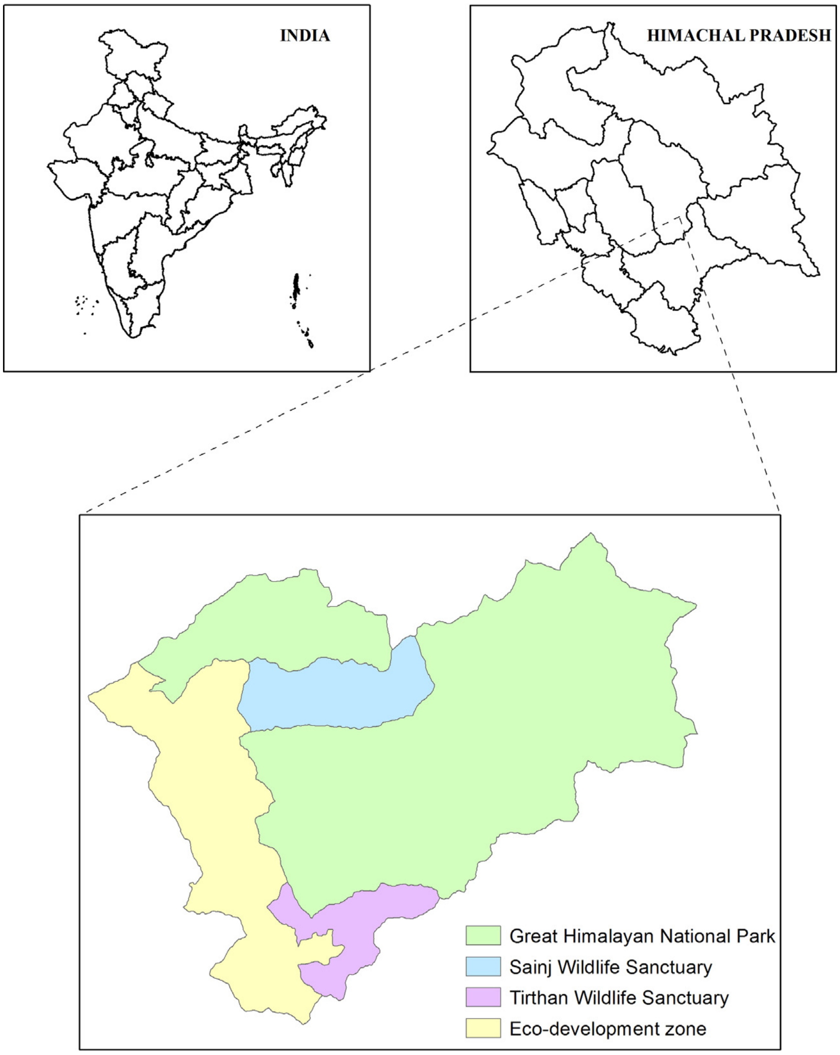
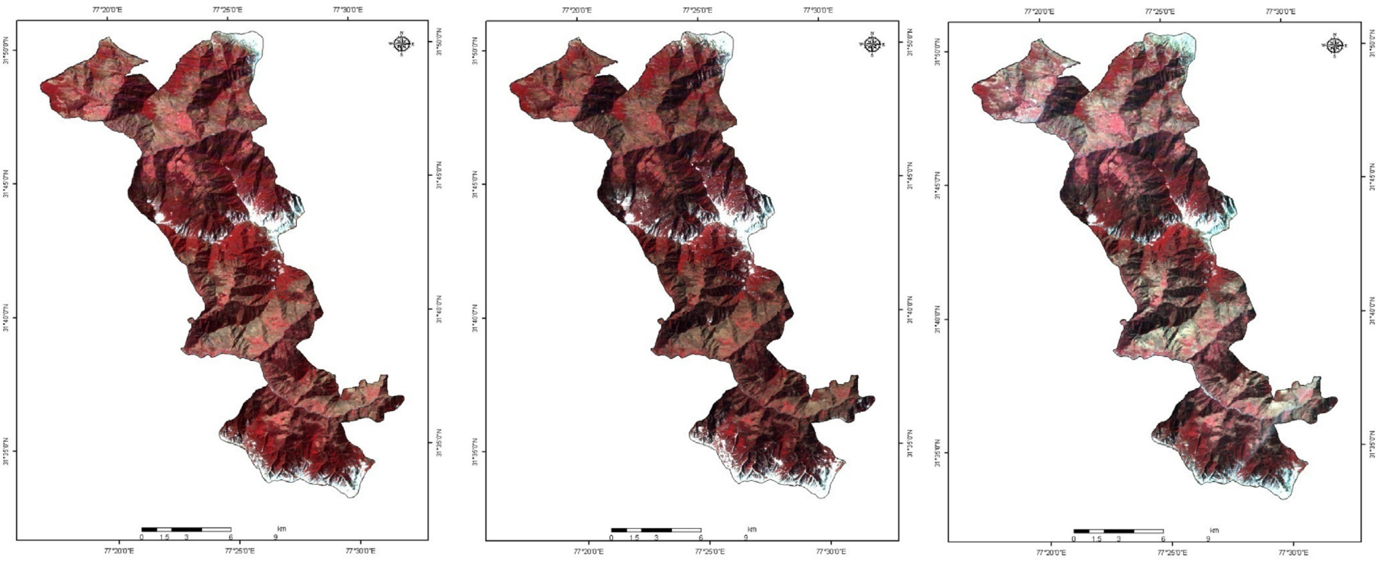


Fig. 1. Location of the study area in India.

Source: www.ghnpkullu.com.



(a) (b) (c)

Fig. 2. Landsat TM satellite imagery of (a) 1990, (b) 2000 and (c) 2010.

Table 1
Fire danger rating (FDR) for different input variables.

S. No.	Land use/land cover	FDR	S. No.	Aspect	FDR
1.	Alpine grassland	2	1.	Flat	1
2.	Barren land	2	2.	North	2
3.	Dam site	1	3.	North-East	2
4.	Chir pine	5	4.	North-West	3
5.	Landslide	1	5.	South	5
6.	Settlement-Agri-Horticulture	1	6.	South-West	4
7.	Snow	1	7.	South-East	3
8.	Temperate broadleaved	3	8.	East	2
9.	Temperate conifers mixed with broadleaved	4	9.	West	3
10.	Temperate mixed conifer	5			
11.	Temperate grasslands and scrub	5	**S. No.**	**Distance (m) to settlements**	**FDR**
12.	Dumping site	1	1.	<1000	5
13.	River	1	2.	1000–2000	4
			3.	2000–3000	3
S. No.	**Forest canopy density**	**FDR**	4.	3000–4000	2
1.	High	2	5.	>4000	1
2.	Medium	4			
3.	Low	5	**S. No.**	**Distance (m) to roads**	**FDR**
4.	Alpine grasslands	2	1.	<1000	5
5.	Barren land	2	2.	1000–2000	4
6.	Dam site	1	3.	2000–3000	3
7.	Landslide	1	4.	3000–4000	2
8.	River	1	5.	>4000	1
9.	Settlement-Agri-Horticulture	1			
10.	Snow	1	**S. No.**	**Elevation (m)**	**FDR**
11.	Temperate grasslands and scrub	5	1.	<2000	5
12	Dumping site	1	2.	2000–2500	4
			3.	2500–3000	3
S. No.	**Slope (Degree)**	**FDR**	4.	3000–3500	2
1.	0–5	1	5.	>3500	1
2.	5–15	2			
3.	15–30	3			
4.	30–45	4			
5.	>45	5			

1 Least, *2* Low, *3* Moderate, *4* High, *5* Very high.

types were stratified into canopy density classes (10–40%-low, 40–70%-medium and >70%-high) using standard visual interpretation approach. The forest canopy density maps were field-verified. Pin hole method was employed for verification of canopy density; a small hole (~0.05 mm) was made into a flat leaf. For estimation of canopy density, one GPS location point was selected. Considering the point as centre, a distance of 20 m was travelled while looking towards the canopy through the hole with every single step in all four directions (north, east, south, and west). The forest canopy density (%) was calculated using following formula (Anonymous, 2009):

$$\begin{aligned}&\text{Forest Canopy Density}\,(\%)\\&\quad = \text{Number of canopy hits}/\text{Total number of steps} \times 100\end{aligned} \tag{1}$$

Fire risk zonation maps of all the three time periods were generated by integrating seven variables, viz., LULC, forest canopy density, slope, aspect, settlement, road and elevation. These geospatial layers were integrated using weights derived from analytical hierarchy process (AHP) (Saaty, 1980). Slope, elevation and aspect maps were derived from ASTER digital elevation model (DEM) while settlements and road network were delineated from the topographic maps and Google Earth images. The Euclidean distance around roads and settlement locations were generated. Each individual geospatial layer was reclassified into five categories viz., very high, high, medium, low and very low according to its impact on fire risk and weights were assigned to each layer.

The fire danger ratings for each individual layer were assigned (Table 1). Very high was given rating five, while very low was given rating one. The different LULC classes were given rating according to their susceptibility to forest fire. The barren land, landslide, settlement-agri-horticulture, dumping site, and snow were given low weight because of their less influence; classes such as grassland and scrub were given higher weights as grasses become dry in dry season thus, becoming more susceptible to fire. The forest classes were given higher weights because forest acts as fuel source for fire. The forest classes rating was based on species types and their response to fire. In the Himalayan region, chir pine is most sensitive to forest fire because of resin content compared to other conifers (Khanna, 1998). The low density forest was given high rating as fuel in these forests dries up during dry season, while medium density and high density forests were given lower rating.

Slope map was classified in to five classes as per slope steepness. Steeper the slope, higher the weight criteria was followed. Higher weights were given to warmer aspects (high solar insolation). Higher elevations were given lower weights while lower elevations were assigned higher weights because of low temperature and higher precipitation at higher elevation. Also at higher elevations, the human interference is less. Road and settlement Euclidean distance maps were classified in to five classes viz. <1000, 1000–2000, 2000–3000, 3000–4000, and >4000 m. Local people commonly travel from 1000 to 4000 m from villages in search of fuel, food, fodder, livestock grazing, and collection of the medicinal plants. Higher weights were, therefore, assigned to the area in close proximity of roads and settlements.

After rating all thematic layers into five classes, AHP-derived weights were generated for each layer. Pair-wise comparison matrix of seven variables viz., LULC, forest canopy density, slope, aspect, settlement, road and elevation was generated (Table 2a) and the priority vectors (Table 2b) were calculated following Saaty (1980). The consistency ratio was found out to be 0.025 which was <0.1, indicating that the calculation was acceptable as per Saaty's principle. The weights of different variables, obtained from the

Table 2a
Pair-wise comparison matrix.

Class	Land use/land cover	Forest canopy density	Slope	Aspect	Road	Settlement	Elevation
Land use/land cover	1	2	3	4	6	7	9
Forest canopy density	1/2	1	2	3	5	7	9
Slope	1/3	1/2	1	2	3	5	8
Aspect	1/4	1/3	1/2	1	2	4	7
Road	1/6	1/5	1/3	1/2	1	2	3
Settlement	1/7	1/7	1/5	1/4	1/2	1	2
Elevation	1/9	1/9	1/8	1/7	1/3	1/2	1
Total	2.45	4.20	7.04	12.68	19.83	28.50	39.00

Table 2b
Synthesized matrix.

Class	Land use/land cover	Forest canopy density	Slope	Aspect	Road	Settlement	Elevation	Priority vector
Land use/land cover	0.399	0.466	0.419	0.367	0.336	0.264	0.231	0.355
Forest canopy density	0.200	0.233	0.279	0.275	0.280	0.264	0.231	0.252
Slope	0.133	0.117	0.140	0.184	0.168	0.189	0.205	0.162
Aspect	0.100	0.078	0.070	0.092	0.112	0.151	0.179	0.112
Road	0.067	0.047	0.047	0.046	0.056	0.075	0.077	0.059
Settlement	0.057	0.033	0.028	0.023	0.028	0.038	0.051	0.037
Elevation	0.044	0.026	0.017	0.013	0.019	0.019	0.026	0.023
								$\Sigma = 1.000$

$\lambda_{\max} = 7.179$, CI = 0.033, RI = 1.32, CR = 0.025 < 0.1 (acceptable).

above analysis, were used in following linear additive model to work out forest fire risk zonation for the three periods:

$$\mathrm{FRZ} = 0.355 \times \mathrm{VTI} + 0.252 \times \mathrm{FDI} + 0.0162 \times \mathrm{SLI} + 0.012 \times \mathrm{ASI} + 0.059 \times \mathrm{RDI} + 0.037 \times \mathrm{STI} + 0.023 \times \mathrm{ELI} \quad (2)$$

where FRZ = Fire Risk Zone, VTI = Vegetation Type Index, FDI = Forest Canopy Density Index, SLI = Slope Index, ASI = Aspect Index, RDI= Road Index, STI = Settlement Index, ELI = Elevation Index.

The landslide susceptibility maps were prepared by Index Overlay Method (IOM). This method is based on expert evaluation of the main influencing factors, which are supported by the site recognitions in the area (Uromeihy and Fattahi, 2011). The seven factors were taken for landslide susceptibility mapping, viz., LULC, slope, geology, aspect, drainage, lineament and road. The geological map was taken from GHNP authority. The LULC, aspect and slope maps were reclassified according to their importance towards the occurrence of landslides. Drainage map was derived from the DEM by using ArcHydro tool of ArcGIS. To incorporate the effect of drainage and roads on landslide susceptibility, a buffer of drainage and road was generated. The lineament map was delineated from the satellite imagery.

The IOM is a knowledge-driven method which depends on the observation of the decision maker. The classes of each input thematic layer were assigned different scores and each layer was assigned ratings according to its contribution towards the landslide susceptibility. All the factor maps were integrated using weights in ArcGIS employing the following equation:

$$S = \frac{\sum_i^n s_{ij} w_i}{\sum_i^n w_i} \quad (3)$$

where w_i is the weight of ith factor map and S_{ij} is the ith spatial class weight of jth factor map and S is the spatial unit value in output map.

The landslide susceptibility rankings and scores were assigned to each class and each individual layers, respectively (Table 3). Very high class was given a rating of five, followed by high (4), moderate (3), low (2), and least (1). It is assumed that forest areas were more stable than other land use classes. The land use classes like dumping site and barren land were given high score because of high risk of landslide. Forest area is assumed to provide stability to the slope and it is widely accepted that vegetation cover has positive influence on slope stability. The major rock type of the area were rated according to their relative importance for landslide. Granites contain k-feldspar which readily alters to clay by chemical and/or mechanical weathering. This is why, in the field, clay is found to be closely associated with granites. However, in case of quartzites with intercalation of minor acidic metavolcanics, mineralogical alteration to clay was inherently arrested. Because of these reasons quartzites provide more resistance to the driving forces, which cause landslides. Buffers of 0–50 m and 50–100 m were created for lineament and areas near 0–50 m was given higher weights, because highly fractured and jointed formation showed higher potential to landslides. Slope map was reclassified in to five classes and according to steepness weights were given. The slope was considered one of the important factors in present study because of complex terrain in Himalayan region. Aspect map was divided in to eight classes and higher weights were given to south, southwest, and southeast aspects because southern aspects are mostly devoid of vegetation or have scant vegetation in Himalayan region. Drainage buffer was also classified into two classes 0–50 m and 50–100 m and more weights were given to 0–50 m class. It was assumed that possibility of landslide frequency is more near streams because of undercutting. Accordingly, proximity to road was assigned higher score. To evaluate the effect of roads on landslide susceptibility, buffers of 0–50 m and 50–100 m were created. The areas near the road were considered more prone to landslide hazards due to higher chances of inappropriate slope cutting-related failure.

The human population census data of 1991, 2001 and 2011 of all the villages situated within the study area were collected from Block Development Office, Banjar, Himachal Pradesh and a village location map with population attributes was prepared. Population density maps were prepared through kriging assuming that distance between points has spatial correlation. The LULC maps, forest canopy density maps, fire risk zonation maps, landslide susceptibility maps and population density maps were generated for 1990, 2000 and 2010 for SPCA-based evaluation. All the factor maps were reclassified into five classes (1–5). The relevant coefficient matrix, R of each variable was established and the eigenvalue of matrix R and its corresponding eigenvectors were computed. This was followed

Table 3
Ranking and score for landslide susceptibility mapping (After Bhoi, 2000).

S. No.	Data layers	Classes	Ranking	Score
1.	LULC	Alpine grassland	7	4
		Barren land	8	
		Dam site	8	
		Chir pine	2	
		Landslide	8	
		Settlement-Agri-Horticulture	6	
		Snow	5	
		Temperate broadleaved	2	
		Temperate conifers mixed with broadleaved	2	
		Temperate mixed conifer	2	
		Temperate grasslands and scrub	7	
		Dumping site	8	
		River	5	
2.	Drainage buffer (m)	0–50	6	4
		50–100	4	
3.	Slope (Degree)	0–5	1	8
		5–15	2	
		15–30	4	
		30–45	7	
		>45	8	
4.	Aspect	Flat	1	7
		North	1	
		North-East	3	
		North-West	3	
		South	8	
		South-West	6	
		South-East	7	
		East	5	
		West	4	
5.	Geology	Granites	4	8
		Quartzite and Meta-volcanic	6	
6.	Road buffer (m)	0–50	6	7
		50–100	4	
7.	Lineament buffer (m)	0–50	6	5
		50–100	4	

by linear grouping of eigenvectors and the computation of principal components. The 'Princomp' function of ArcGIS was used for data stacking from input multivariate attributes space to new multivariate attribute space. The impact of every factor on evaluation was graded as:

$$E = a_1Y_1 + a_2Y_2 + \ldots + a_iY_i \tag{4}$$

where Y_i is number of ith principal component, while a_i is its corresponding contribution ratio. Weights for each component were computed using Eq. (4).

The result computed showed continuous values, which were classified into five classes, viz., potential, slight, medium, high and severe vulnerability representing different environmental vulnerability status. Based on the gradation of vulnerability for different levels, the change in trend from 1990 to 2000 and from 2000 to 2010 was analyzed based on environmental vulnerability integrated index (EVSI) (Li et al., 2006a):

$$\mathrm{EVSI}_j = \sum_{i}^{n} P_i \times \frac{A_i}{S_j} \tag{5}$$

where n is number of valuation grade, EVSI_j is the EVSI unit in j, A_j the occupied area of grade i in analysis unit j, S_j the area of analysis unit j, P_i is the graded value of grade i.

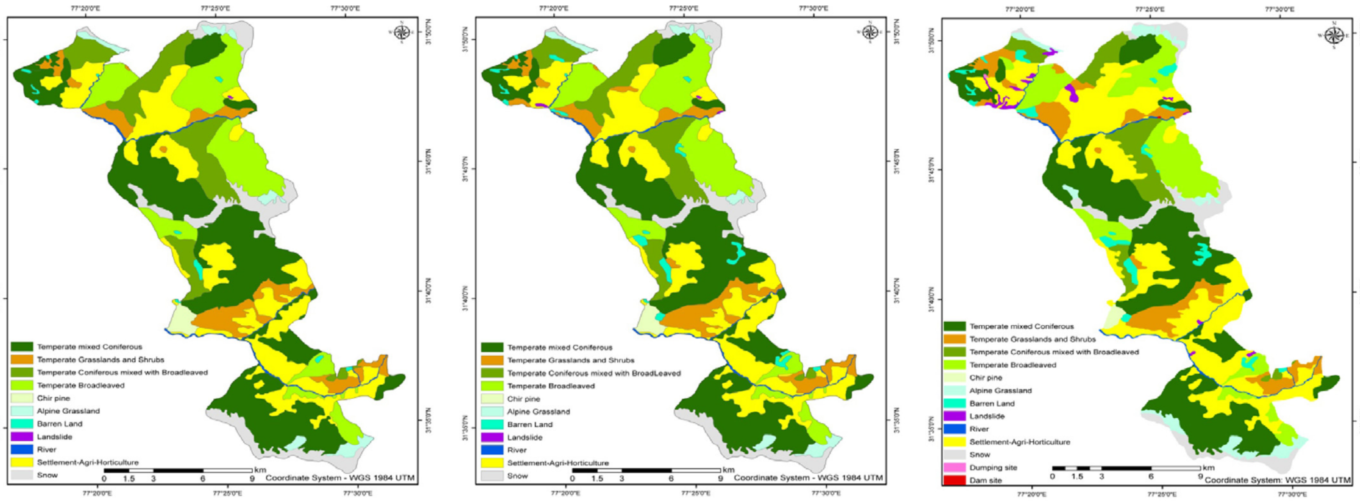
The distribution of environmental vulnerability for each level and time period was evaluated from calculated EVSI values. For the accurate evaluation of environmental vulnerability, the contribution of each factor was calculated. Eq. (6) was used to calculate the contribution of each factor to environmental vulnerability for the year 2010.

$$\text{Contribution of Factor} = \frac{\sum_{j=1}^{5} \mu_I^J \times \lambda_J}{\sum_{I=1}^{5} \times \sum_{j=1}^{5} \mu_I^J \times \lambda_J} \tag{6}$$

where λ is eigenvalue and μ is the corresponding eigenvector.

3. Results and discussion

Five factors, viz., LULC, forest canopy density, forest fire risk, landslide susceptibility and human population density were considered for the assessment of environmental vulnerability of eco-development zone of GHNP. Thirteen LULC classes were interpreted, viz., alpine grasslands, barren land, chirpine, landslide, river, settlement-agri-horticulture, snow, temperate broadleaved, temperate broadleaved mixed with conifers, temperate mixed conifers, temperate grasslands and scrub, dumping site and dam site. During 1990 and 2000, there were 11 LULC classes and in 2010 two more classes were added (Fig. 3). The overall accuracy of the LULC map of 2010 was 88.72 percent ($k_{\mathrm{hat}} = 0.88$). In 1990, total forest area was 60.81 percent, and the dominant forest classes were temperate mixed conifers (32.81%) followed by temperate broadleaved (16.8%), and temperate coniferous mixed with broadleaved (10.92%). In 2000, the total forest area decreased to 57.35 percent and it further decreased to 50.40 percent in 2010. A significant loss of 3.47 percent forest area from 1990 to 2000 and 6.95 percent during 2000 to 2010 was observed (Table 4). This may be attributed to the developmental activities. There were increases



(a) (b) (c)

Fig. 3. Land use/land cover map of (a) 1990, (b) 2000 and (c) 2010.

in area under settlement-agri-horticulture, landslide, barren land, temperate grasslands, and scrub. During 1990–2000 period, the area under settlement-agri-horticulture increased by 1.44 percent. It further increased by 5.05 percent during 2000–2010. This change is due to agricultural intensification and unplanned urbanization. The unplanned urbanization further increased because of development activities, especially construction of hydro-electric project from 2000 to 2010. The most significant changes took place in forest and settlement-agri-horticulture class; where forest cover declined with corresponding increase in settlement-agri-horticulture and other human-managed systems.

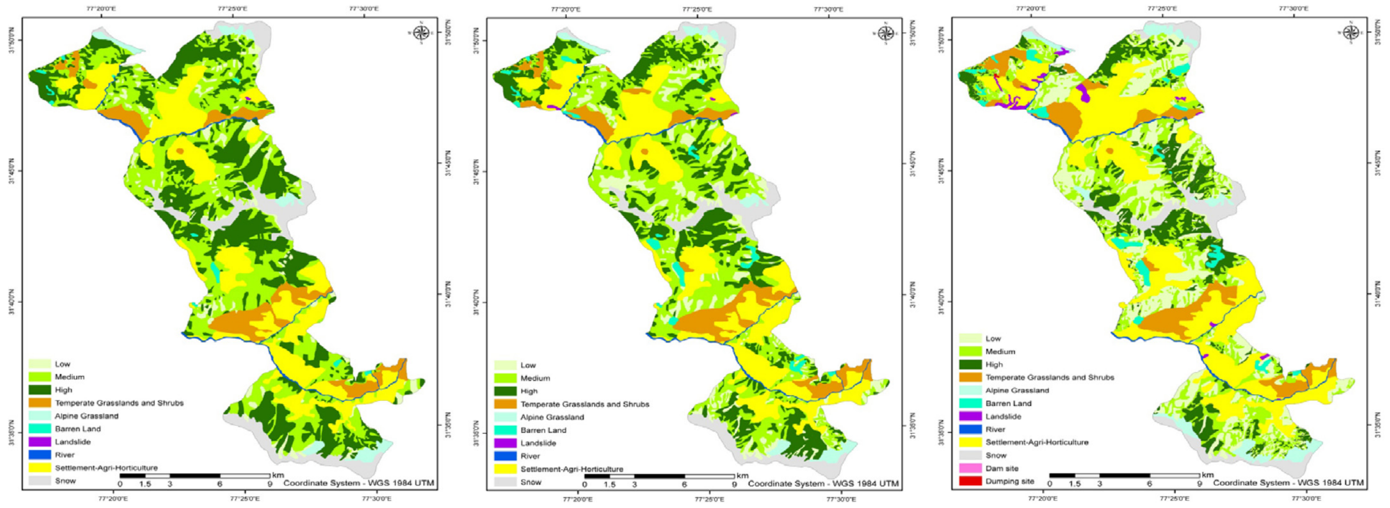
The conversion of natural forest cover to other land use results in fragmentation and degradation of forest and loss of habitat of many floral and faunal species, which is strongly related to the environmental vulnerability. Mathur and Naithani (1999) also reported an increase of 9 km^2 under habitation/agriculture/orchard with a corresponding decline of about 4 km^2 of forest area between 1961 and 1993 in GHNP. This change has devastating impact on the local ecosystem services.

Forest canopy density maps for the three time periods 1990, 2000 and 2010 were generated (Fig. 4). The overall accuracy of the forest canopy density map of 2010 was 89.69 percent ($k_{hat} = 0.88$). In 1990, the high density class occupied 26.81 percent, medium 29.30 percent and low 4.93 percent. Area under high density class decreased to 19.07 percent in 2000 followed by 12.4 percent in 2010 (Table 5). Medium density class also showed decreasing trends in the corresponding periods. Low density forest during 2000–2010 increased to 19.2 percent. The decreasing trend of forest canopy density can be attributed to the increased human interference in forest areas for extraction of various forest resources like fuel wood collection, seasonal collection of medicinal herbs and illegal felling of tree for furniture wood. Forest canopy density is an essential parameter to assess the ecological conditions of the any area (Nandy et al., 2003) and have been used to indicate the degradation status of forest (Tiwari et al., 1986; Nandy et al., 2011). Continuous decrease in forest canopy closure leads to fragmentation and degradation of forest, and loss of habitat which directly affects the local ecosystem. Hence, the forest canopy density is an important factor in the context of environmental vulnerability in the study area.

The forest fire risk zonation maps (Fig. 5) showed that the area under very high risk zone increased from 11.18 percent in 1990 to 16.64 percent in 2000 and 25.81 percent in 2010 (Table 6). Area under least fire risk decreased from 30.24 percent to 28.73 percent in 2000 and further decreased to 21.72 percent in 2010. Increasing trend in very high class and decreasing trend in least fire risk class may be attributed to the increasing activities of the people in forest area. In dry summer season, when forests are most susceptible to fire, shepherds move from plains to higher mountains in study area for livestock grazing. Tourism and trekking activities have also increased considerably; unextinguished camp fires of trekkers and

Table 4
Area under different land use/land cover classes during the study periods.

S. No.	Land use/land cover	Area (km^2)		
		1990	2000	2010
1.	Chir pine	2.65	2.40	1.30
2.	Temperate mixed conifer	86.63	81.17	74.34
3.	Temperate conifer mixed with broadleaved	28.82	26.49	21.39
4.	Temperate broadleaved	42.45	41.35	36.02
5.	Temperate grasslands and scrub	18.55	20.52	21.62
6.	Alpine grassland	5.41	5.64	8.59
7.	Snow	20.31	20.22	16.70
8.	River	2.85	2.85	2.82
9.	Settlement-Agri-Horticulture	54.93	58.74	72.07
10.	Barren land	1.35	4.38	6.65
11.	Landslide	0.05	0.25	2.41
12.	Dam site	0.00	0.00	0.04
13.	Dumping site	0.00	0.00	0.06
	Total	264.00	264.00	264.00



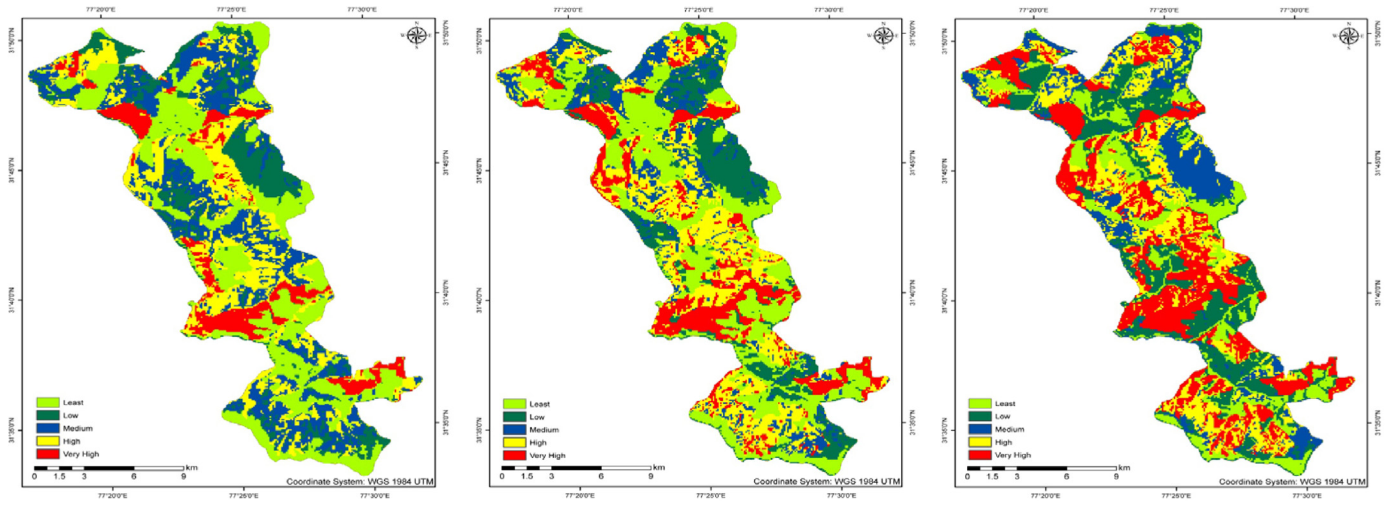
(a) (b) (c)

Fig. 4. Forest canopy density map of (a) 1990, (b) 2000 and (c) 2010.

Table 5
Area under different forest canopy density and land uses.

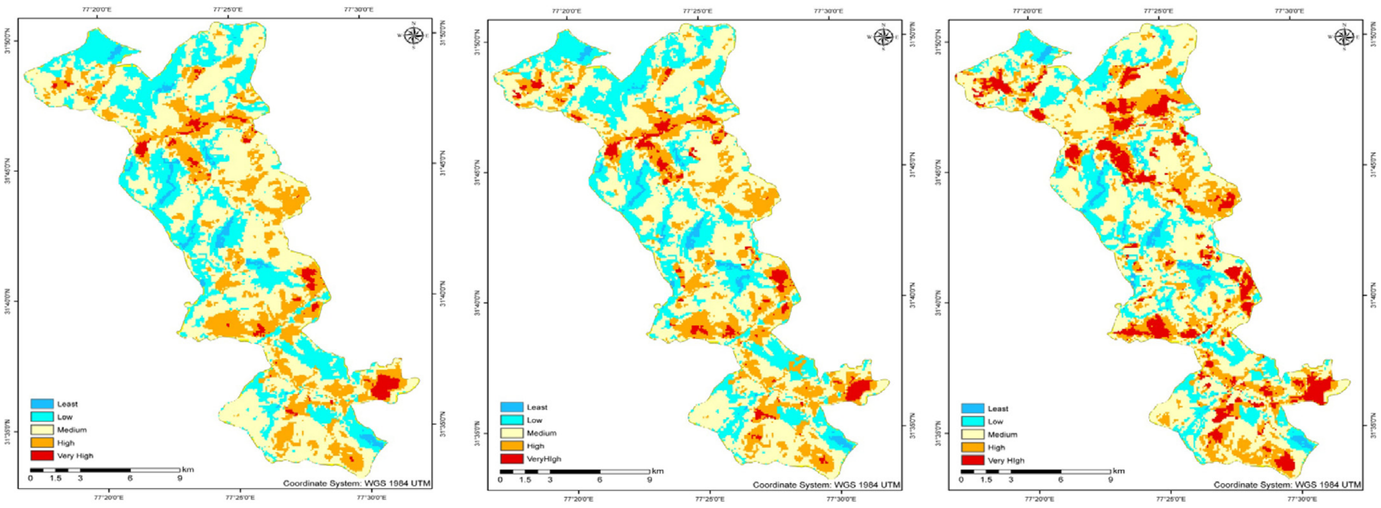
Sl. No.	Forest canopy density	Area (km^2)		
		1990	2000	2010
1	High density (>70%)	70.79	50.35	32.87
2	Medium density (40–70%)	77.35	76.72	49.37
3	Low density (10–40%)	12.41	24.33	50.81
4	Temperate grasslands and scrub	18.55	20.52	21.62
5	Alpine grassland	5.41	5.64	8.59
6	Snow	20.31	20.22	16.70
7	River	2.85	2.85	2.82
8	Settlement-Agri-Horticulture	54.93	58.74	72.07
9	Barren land	1.35	4.38	6.65
10	Landslide	0.05	0.25	2.41
11	Dam site	0.00	0.00	0.04
12	Dumping site	0.00	0.00	0.06
	Total	264.00	264.00	264.00

shepherds spread accidently and convert into forest fires. Unextinguished cigarettes butts and matchsticks also lead to accidental forest fire. Sometimes forest fire can spread due to unchecked burning operations carried out in adjacent agricultural fields. Trees and shrubs get severely affected by the forest fire; sometimes whole forest and grasslands can be destroyed in short period of time, this has very adverse effect on the growth and productivity of forest. As in the areas damaged by the forest fire, soil is exposed thereby



(a) (b) (c)

Fig. 5. Forest fire risk zonation map of (a) 1990, (b) 2000 and (c) 2010.



(a) (b) (c)

Fig. 6. Landslide susceptibility maps of (a) 1990, (b) 2000 and (c) 2010.

Table 6
Area under different forest fire risk zones during the study periods.

S. No.	Forest fire risk zones	Area (km^2)		
		1990	2000	2010
1.	Very high	29.51	43.93	68.15
2.	High	62.64	63.92	64.53
3.	Moderate	38.91	33.89	30.15
4.	Low	53.12	46.41	43.83
5.	Least	79.83	75.86	57.33
	Total	264.00	264.00	264.00

Table 7
Area under different landslide risk zones during the study periods.

S. No.	Landslide risk zones	Area (km^2)		
		1990	2000	2010
1	Least	4.90	4.75	4.66
2	Low	65.68	65.35	49.21
3	Moderate	128.91	126.06	125.21
4	High	57.65	57.33	57.30
5	Very high	6.86	10.53	27.62
	Total	264.00	264.00	264.00

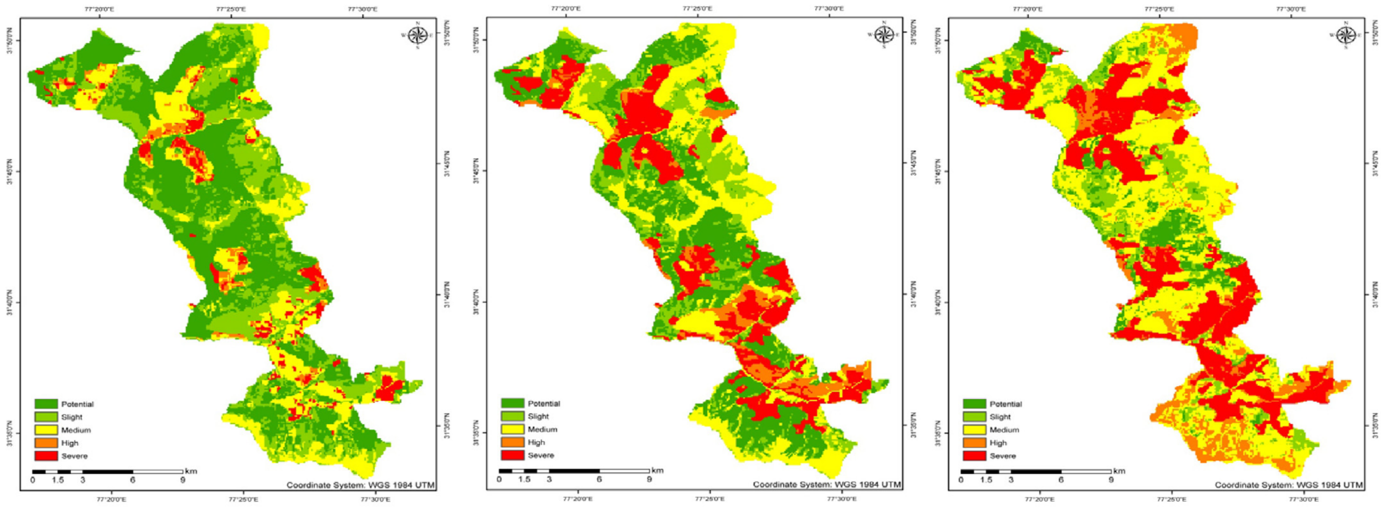
increasing the chances of soil erosion (Kandya et al., 1998). Fire also affects the fertility of the soil and may cause destruction of habitat of wild animals to a large extent. The western Himalayan coniferous forests are very prone to fire and being ecologically sensitive, the impact of fire on forest and environment is long lasting, irreversible and beyond repair (Anonymous, 2005). Forest fires also produce carbon dioxide, carbon monoxide, methane and other greenhouse gases and a lot of smoke chocking nearby settlements. Hence, in the context of the Himalayan region, forest fire becomes one of the most important environmental problems.

The human population density shows an increasing trend over the period under study. Total population of study area was 10,131 persons in 1991 which increased to 12,610 persons in 2001 and further increased to 15,580 persons in 2011. The effects of population growth are varied and vast in the study area. The increasing population around the study area has caused adverse impacts on the local environment. The resource requirements of a growing population lead to the depletion of natural resources and rapid land use changes. As local people are heavily dependent on the fuel wood; extraction of fuel wood from the forest has increased drastically leading to the degradation of forests. Agricultural areas have expanded considerably in the Himalayan region to sustain a growing population (Rao and Pant, 2001). Over-grazing and illegal timber harvesting have resulted in the environmental degradation. Additionally, there is gradual migration of population from other areas for employment in the hydroelectric projects and the migrant population has added pressure on local ecosystems.

The landslide susceptibility maps (Fig. 6) showed that area under very high risk zone increased from 2.60 percent in 1990 to 10.46 percent in 2010 (Table 7). The increase in area of very high risk

Table 8
Spatial principal component analysis (SPCA) during 1990, 2000 and 2010.

Principal Components	I	II	III	IV	V
2010					
Eigenvalue	1.2907	0.50236	0.43444	0.19827	0.15619
Contribution ratio (%)	49.92	19.43	16.80	7.67	6.18
Cumulative ratio (%)	49.92	69.35	86.15	93.82	100
2000					
Eigenvalue	1.3028	0.50236	0.4264	0.2118	0.1120
Contribution ratio (%)	51.10	19.63	16.66	8.27	4.34
Cumulative ratio (%)	51.10	70.72	87.38	95.66	100
1990					
Eigenvalue	1.3292	0.5255	0.4125	0.2350	0.1016
Contribution ratio (%)	51.05	20.18	15.84	9.03	3.90
Cumulative ratio (%)	51.05	71.23	87.07	96.10	100



(a) (b) (c)

Fig. 7. Environmental vulnerability maps of (a) 1990, (b) 2000 and (c) 2010.

zone may be attributed to the construction of roads and increased developmental activities. In the study area new road construction is aggravating the risk of landslide occurrence. Chandel et al. (2011) reported that 32 percent area of Kullu district comes under severe zone for landslide, only 19.42 percent comes under moderate and 0.42 percent area under low or no risk. Landslides increase soil erosion and sedimentation. The impact of landslides on forest and wildlife are mostly adverse. In the study area, the landslide-related disturbances are continuous and increasing, which may not allow ecosystem recovery. In recent decades human activities have contributed immensely in slope failure in Himalayas (Haigh et al., 1989). The landslides studies using remote sensing and GIS showed that landslides are one of the frequently occurring natural hazards in Kullu district with massive destruction of life and property and sometime lead to large-scale landscape transformations (Chandel et al., 2011).

On the basis of confirmed principal components and using Eq. (4) the integrated evaluation index was computed for three time periods under study (Table 8).

$$\begin{aligned}\mathrm{EVI}\,2010 = {} & 1.2907 \times \mathrm{P1} + 0.50236 \times \mathrm{P2} + 0.43444 \times \mathrm{P3} \\ & + 0.19827 \times \mathrm{P4} + 0.15619 \times \mathrm{P5} \end{aligned} \tag{7}$$

$$\begin{aligned}\mathrm{EVI}\,2000 = {} & 1.3028 \times \mathrm{P1} + 0.50236 \times \mathrm{P2} \\ & + 0.4264 \times \mathrm{P3} + 0.2118 \times \mathrm{P4} + 0.1120 \times \mathrm{P5} \end{aligned} \tag{8}$$

$$\begin{aligned}\mathrm{EVI}\,1990 = {} & 1.3292 \times \mathrm{P1} + 0.5255 \times \mathrm{P2} \\ & + 0.4125 \times \mathrm{P3} + 0.2350 \times \mathrm{P4} + 0.1016 \times \mathrm{P5} \end{aligned} \tag{9}$$

Table 9
Environmental vulnerability gradation.

Evaluation level	Number	EVI
Potential vulnerability	I	<1.40
Slight vulnerability	II	1.40–2.33
Medium vulnerability	III	2.33–3.10
High vulnerability	IV	3.10–3.99
Severe vulnerability	V	>3.99

The outcomes calculated from EVI are continuous values and these were classified into five classes, viz., potential, slight, medium, high and severe vulnerability, based on the distribution of histogram. Grouping was done by considering the breaks which had uniform values and where boundaries were distinct (Table 9). The same approach was used by Li et al. (2006a,b) and Hyandye et al. (2008). The EVI values <1.40 was classified as potential followed by 1.40–2.33 as slight vulnerability, 2.33–3.10 as medium vulnerability, 3.10–3.99 as high vulnerability and >3.99 as severe vulnerability.

The area under environmental vulnerability class-I (Fig. 7) decreased from 1990 (44.07%) to 2010 (7.93%) (Table 10). The class-II showed same trend. The corresponding area under class-III increased over the years. The percentage of area under class-IV and class-V increased considerably from 1990 to 2010. In 1990, the area under class-V was only 5.73 percent which increased to 20.85 percent by 2000 and registered further increase (28.68%) by 2010. In 1990 EVSI value was 2.0, for 2000 it was 2.72 and for 2010 it was 3.40. The EVSI values indicate that environmental vulnerability is increasing in the study area (Table 10). This proves that environmental condition in study area are changing. The highest contributing factor to the environmental vulnerability

Table 10
EVSI during different time periods.

Time period	1990			2000			2010		
Environmental vulnerability class	Grid number	Percentage	EVSI	Grid number	Percentage	EVSI	Grid number	Percentage	EVSI
I	19,762	44.07		40,874	29.30		3555	7.93	
II	12,069	26.92		25,607	18.36		5942	13.25	
III	9036	20.15	2.00	34,123	24.46	2.72	17,035	37.99	3.40
IV	1566	3.49		9817	7.04		5448	12.15	
V	2408	5.37		29,080	20.85		12,858	28.68	

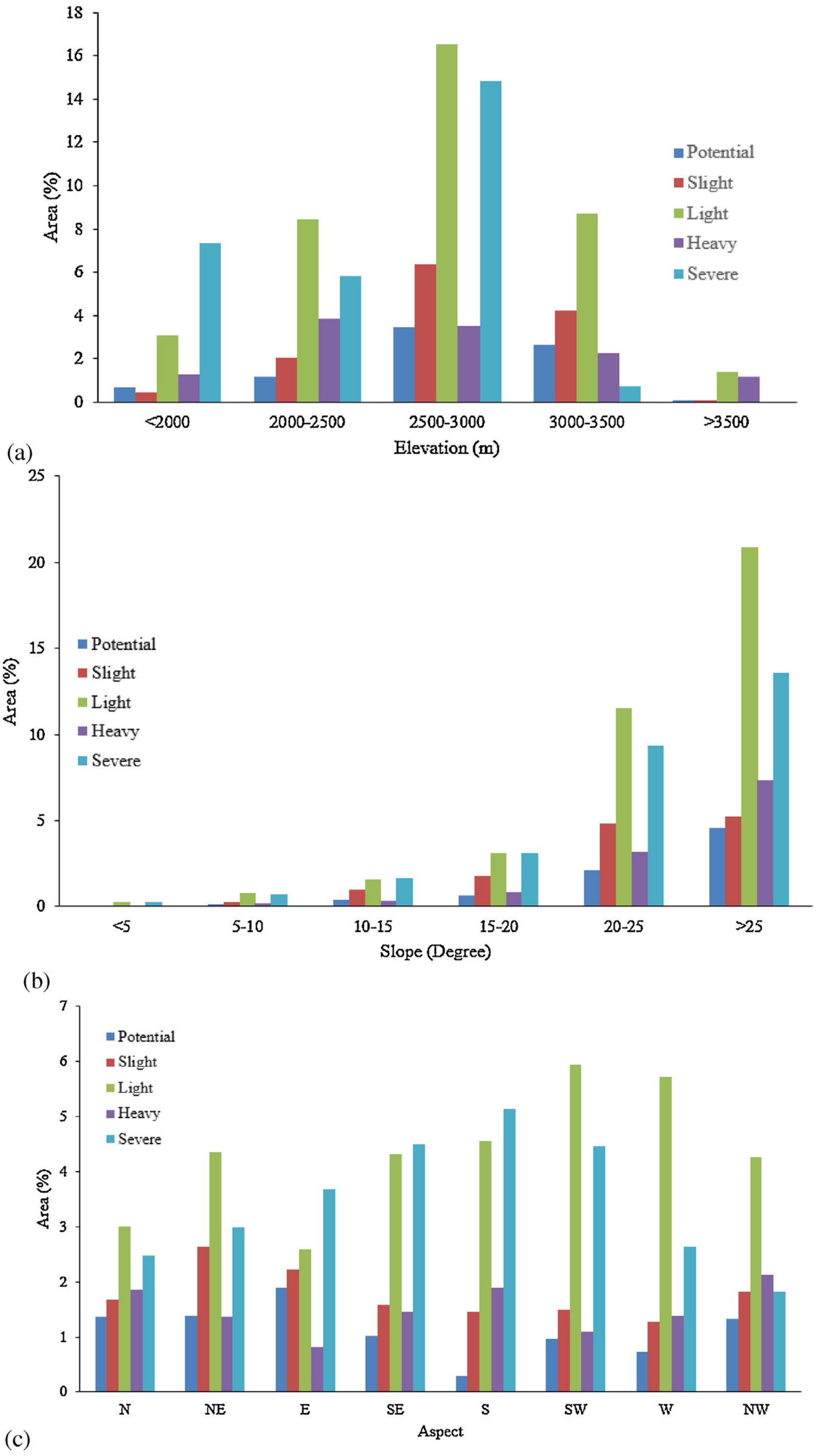


Fig. 8. Environmental vulnerability levels distributed along (a) altitude, (b) slope and (c) aspect.

was LULC (27.21%) followed by forest fire (25.86%), forest canopy density (19.39%), population density (14.11%) and landslides (13.44%) (Table 11). Thus, it is clear that the LULC, forest fire and forest canopy density are the dominant factors. The driving force responsible for the increased land use is the intensification of human activities from 1990 to 2010.

It was observed that most of the area under severe, high and medium vulnerability comes under the elevation ranges, <2000 m, 2000–2500 m and 2500–3000 m (Fig. 8). Reason for this distribution is that the human activities such as agriculture, horticulture, collection of fuel wood and fodder, hydro-electric projects, road network and settlements are restricted in these elevation ranges. Vulnerability was found to be lower at higher elevations due to less human activities. The environmental vulnerability was more robust in east, south east, south west and western aspects; area under low environmental vulnerability classes was more in north, northwest and northeast aspects (Fig. 8), this can attributed to increased human activities on the warmer aspects. The maximum

Table 11
Contribution of each factor to environmental vulnerability.

Factors	Principal components					Contribution (%)
	I	II	III	IV	V	
	Eigenvalue					
	1.2907	0.50236	0.43444	0.19827	0.15969	
	Eigenvectors					
Landslide	0.62923	−0.32447	−0.53453	−0.26450	0.37855	13.44
Forest canopy density	0.28392	0.05232	−0.00442	0.93198	0.22016	19.39
LULC	0.65453	0.01585	0.28103	−0.33470	−0.7008	27.21
Forest fire	0.27854	0.20176	0.71609	−0.22654	0.56305	25.86
Population density	0.13216	0.92223	−0.3928	−0.09879	0.00883	14.11
Total						100

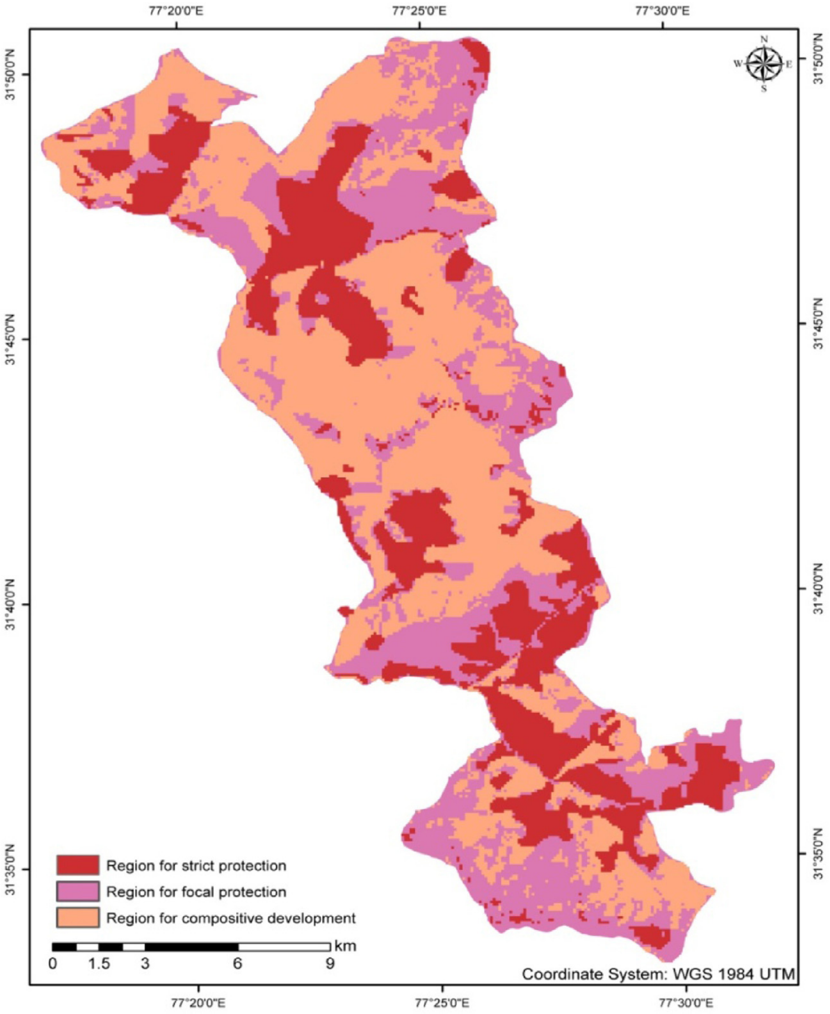


Fig. 9. Regionalization of vulnerability.

area of severe vulnerability was observed in southern aspect of the study area. High environmental vulnerability was observed in steeper areas, while environmental vulnerability was low in relatively less steep slopes (Fig. 8) because of high landslide potential and developmental activities.

4. Conclusions

The overall aim of the study was to assess the environmental vulnerability of the study area. The environmental vulnerability showed distinct spatial distribution in the study area. It is more in lower and middle elevation ranges, because most of the human activities are restricted to these regions. South, east, southeast, southwest and western aspects possess high environmental vulnerability. The high environmental vulnerability was also observed on steep slopes. As evident from the EVSI values obtained from the study, the environmental vulnerability of the study area has increased considerably during the study period. The EVSI in 1990 was 2.00 which increased to 2.72 in 2000 and further to 3.40 in 2010. The increase in the environmental vulnerability may be attributed to the on-going construction of hydro-electric power projects within and close proximity to the study area, coupled with increasing road network and destruction of natural resources due to anthropogenic pressure, forest fire and landslides. LULC, forest fire and forest canopy density contributed more to environmental vulnerability. Hence it can be concluded that these are the major factors responsible for increased environmental vulnerability in the study area.

In order to suggest alternative measures to GHNP authority and to make results effective for practical application to the recovery of the local ecosystem, a few measures can be suggested. The environmental vulnerability assessed in the present study can be categorized into three regions of protection, viz., region of strict protection, region of focal protection and region of composite development (Fig. 9). Li et al. (2006a) also suggested protection zones in the upper reaches of Minjiang River, China.

Region of strict protection: The region where environmental vulnerability is severe is identified as the region of strict protection. This region constitutes 25.81 percent (68.15 km^2) of the total area. Considering the status of the area, all the development activities must be effectively monitored by the authority, and a proper reclamation plan for ecological recovery should be immediately put in place. Also comprehensive strategy for combating forest fire hazard should be implemented. Human activities should be barred in this region.

Region of focal protection: Area under light and medium vulnerability constituting 29.05 percent (76.68 km^2) of the total area is suggested for focal protection. In this region the improved implementation of conservation measures is needed. This can be achieved by providing alternative sources of income to local people. Active participation of the local people in eco-restoration is recommended.

Region of composite development: Slight vulnerability region constitutes 45.14 percent 9119.17 km^2) of the total study area and is recommended for composite development. In this region, human activities should be reduced as much as possible and eco-restoration activities should be initiated immediately.

The study highlighted that remote sensing, GIS and SPCA can be effectively integrated to quantify and assess the environmental vulnerability. The approach can be applied over large area for rapid assessment of the environmental status.

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