Landslide Hazard Assessment Using Probabilistic and Statistical Approaches: A Case Study of Chamba Region, Himachal Pradesh, India

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LANDSLIDE HAZARD ASSESSMENT USING PROBABILISTIC AND STATISTICAL APPROACHES: A CASE STUDY OF CHAMBA REGION, HIMACHAL PRADESH, INDIA

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ABSTRACT

Landslides have adversely affected the southern region of Chamba district during past three decades. To minimize the damage to ecology and environment due to such natural calamities, landslide hazard zonation and mitigation measures are essential component to stabilize the natural slopes and other physiographic features. In order to remodeling lopsidedness in study area analytical hierarchy process and information value methods with applications of remote sensing and geographic information system (GIS) are utilized to delineate the most recumbent landslide hazard zones. Eleven-factor maps like slope gradient, slope aspect, relative relief, land use/ cover etc., were delineated using different sets of data like satellite images and field investigations etc. Depending upon the severity, landslide hazard maps (LHZ) were further divided based upon information value method and analytical hierarchy process models respectively, into five different categories very low (1.2% and 2.95%), low (5.31% and 4.27%), moderate (24.40% and 20.03%), high (29.26% and 31.03%), and very high (40.30% and 44.2%). These hazard maps obtained through both information value and analytical hierarchy process (AHP) were compared for accuracy using success rate curve (SRC) method. Accuracy of the hazard zonation maps was found to be 78.62% for AHP and 85.17% for Inf. Value models.

Keywords: Middle Himalayan, National Highway, hazard, Mapping, Successive rate curve.

Introduction

Landslide is a significant environmental risk, instigating destruction to life and infrastructure. Several authors categorize landslides such as: fall, topple and flow, spread, slide etc. in terms of rock, debris, and earth under the influence of the gravitational forces in the downward and outward direction of the slope (Varnes and IAEG, 1984; Crozier 1986; Couture 2011). The strength of the slope forming materials and slope angle controls the stability of the slope. Past landslide records, intensive field work and professional experience play important role in the selection of the essential factors. The Indian states of Jammu and Kashmir, Himachal Pradesh, Uttarakhand, and Sikkim often get disturbed due to landslides during every monsoon. Districts like Chamba, Kangra, Mandi, Kullu, Bilaspur, and Shimla are highly affected by landslides in the state of Himachal Pradesh. Hence, a vulnerable stretch from Lahru to Chamba along NH-154A via Banikhet was selected for LHZ assessment in the present study. Landslides associated with the river beds are affected due to the undercutting of the toe of slopes. The economy of Himachal Pradesh and Government of India is adversely affected by these slope failures and in some cases many lives were also lost. Mitigation and remedies for the slope failures in study area has been useful after identification of landslide hazard zones.

The mountainous terrain of district Chamba in Himachal Pradesh is suffering from landslide disaster mainly in the region where slope gradient is greater than 40° which is harming lives and million dollars property across the region. An earthquake triggered landslides caused death of around 500 people in Chamba in year 1905. The inherent and extrinsic landslide causative factors like geomorphological, geological, hydrology, soil, landuse land cover (LULC), rainfall, seismic etc. play important role for causing landslide movement (Cruden and Varnes 1996; Courture 2011) from which the geology, soil, and LULC are the major factors contributing in landslides (Varnes 1984; Anbalagan 1992; Hutchinson 1995; Achour et al. 2017). The constructional activities of infrastructural mega projects are also disturbing hilly terrains in this region. Hence, the landslide hazard assessment is essential in the region for future development and construction.

A minimal work has been found on the landslide hazard assessment using GIS in present study area based on the qualitative (Probabilistic) and quantitative (Statistical) approaches. The qualitative methods like landslide hazard evaluation factor (LHEF) (BIS code 1998) and analytical hierarchy process (AHP) (Saaty 1980) were widely adopted in literature (Sudhakar and Pardeshi et. al. 2013) by geologists and geotechnical engineers during year 1970 to 1980 (Aleotti et. al 1999). The matrix formation form pairwise comparison through the desired weight values

based on experts experience are essential components for qualitative analysis in AHP for LHZ assessment. The quantitative methods for LHZ assessment generally depends upon the percentage of the landslide and landslide controlling factors. Statistical (information value, frequency ratio, weight of evidence etc.) and deterministic methods (fuzzy logic, logistic regression, and artificial neural network etc.) are the example of quantitative methods (Ercanoglu and Gokceoglu, 2002; Suzen and Doyuran, 2004; Ercanoglu and Gokceoglu, 2004; Yesilnacar and Topal, 2005; Kanungo et al., 2006; García-Rodríguez et al., 2008; Nefeslioglu et al., 2008; Nandi and Shakoor, 2009; Dongyeob Kim et al., 2010; Pradhan B., 2012). Distribution of landslide events and landslide controlling parameters are correlated with historical events by using statistical methodology (Refice and Capolongo, 2002; Zhou et al., 2003). The influence of rainfall has also been analyzed in terms of thresholds for triggering landslides by various researchers (Iverson 2000; Crosta and Frattini 2003; Brooks et al. 2004; Montrasio et al. 2012; Salciarini et al. 2012; Ran et al. 2012; Marchi et al. 2002; Floris et al. 2004; Giannecchini 2005; Kanungo and Sharma 2014; and Chung et al. 2016).

Figure 1: Photographs of critical slopes taken during March 2019 field visit along SH28 and NH -154A (a) Earth debris failure 500m from Lahru at SH28 (b) Transitional and Rock debris landslide near Chowari at SH28, (c) Debris flow landslide neat Jot at SH28 (d) Rock fall and Earth flow landslide 250m before Ghatasani bridge at NH145-A (e) Earth Debris flow landslide near Banikhet at NH-154A (f) Rock fall landslide near Chamba at NH154A.

Study area

Study area covers 27355.47 m² area enveloped between 80.84 Km NH-154A from Lahru to Chamba via Banikhet (76°10'E, 32° 35'N) and 54.90 Km along the state highway 28 from Lahru to Chamba via Jot (75° 51' E, 32 ° 26' N). The area has a dendritic drainage pattern and can be easily identified on using Survey of India 1986 topographic sheets (43P/14, 43P/15, 52D/2 and 52D/3) on the scale of 1:50,000. The study area has high relief with altitude ranging from 656 feet near Lahru to 2757 feet in Dalhousie. Maximum temperature in summer is 30°C whereas minimum is 14°C while in winter season temperature varies between 2°C to 11°C. Rainfall of 186.42mm was recorded during the year 2018 in this region (Indian meteorological department).

Climate conditions and physiography are the root cause of slope failures in the study area. On 2nd August 2018 one bus was washed out and road was blocked for the almost one day reported in several local newspapers and media. During the monsoon period of 2017 and 2018 landslide measuring 434m length and 136m wide has taken place below the Bindgi village, Bhattiyat tehsil near hair pin bend (75°57'11.70"E, 32°26'19.21"N to 75°57'16.49"E, 32°26'20.11"N and 75°57'12.99"E, 32°26'17.81"N to 75°57'16.83"E, 32°26'19.33"N). Mountain slopes are affected by human interferences for development and unplanned construction although rainfall and seismic activities also play vital role for triggering landslides. Transitional landslide was found along NH-154A at a distance of about 250m Ghatasani Bridge damaging around 800 m road stretch as reported by Hindustan, Times of India and as per records of H.P Public Works Department. Debris flow caused damage to NH nearby 500m from Lahru at July 14, 2017 as reported by the Tribune and Times of India. Road construction initiated huge translational slide due to movement of thrust near Chowari has also been reported (Singh and Thakur 1989, Keshar Singh 2011).

Figure 2: Study area Lahru to Chamba, Chamba District, and Himachal Pradesh, India

Geological Setting

Regional geological setup in study area consists of a large syncline called Chamba syncline, having meta-sedimentary rocks with 8-10km thickness belonging to Cambrian to Triassic era. Subordinate phyllites with laminated cross-bedded quartzite are main subsistence of the Chamba formations. Phyllites, slates and limestones are foundation of the Shali formation which is overlain by the alluvium. PindruFormation rock bodies are subsistence with interstratified schist, quartzite, staurolite, schist and conglomerate. KhokanFormation rock bodies are surrounded by Vaikrita thrust. Kalhel rock bodies of Kalhel formation (Lilang Group) is found in pockets which were overlaid by GharFormation. Upper Siwaliks rock bodies are youngest formation of rocks in the region shown in Table 1. Tectonic activity of the region is the cause of frequent the seismic activities in the region. Seismic activity of 6.5 magnitude in year 1945 near Chamba town, massive landslides were occurred at various places i.e. Chamba, Jot, Chowari, Banikhet, and Darada etc. Earthquake of 6.2 magnitudes in 1947 played vital role in activation of slope failure 1km short of Chowari. Subsequent earthquake varying 4 to 4.5 magnitude in 1950, 1955 and 2005 triggered some slope failures likely near Banikhet 500m before Chamba District (Sharma et al. 2005). Amateur seismic center (Pune, Maharastra), based on the earthquakes records put Chamba region in Zone V. Lesser Himalayan lies in a wide zone which is located in between the “main boundary thrust (MBT) and main central thrust (MCT)” that runs along the base of the frontal range (Deeken et al., 2011).

Table 1: Geological succession of study area (Ratan SS (1973), Thakur VC and Rawat BS (1992) and Geological wing, department of industries, government of Himachal Pradesh)

Era	Origin	Formation	Group	Rock types
Recent/Holocene	Sedimentary	Alluvium		
-----Vaikrita Thrust (VT) -----				
Upper Pliocene to lower Pleistocene	Sedimentary	Siwalik	Upper Siwalik	Coarse sandstones, conglomerates, coarse boulder, clays, sands and grits
			Middle Siwalik	Coarse micaceous Sandstones with interbeds of earthy clay
			Lower Siwalik	Sandstones –clay alternation
Lower Miocene	Sedimentary	Dharmasala formation	---	Coarse micaceous Sandstones with inter beds of earthy clay
Middle Miocene	Sedimentary	Khalel formation	Lilang Group	Sandstones –clay alternation
Lower Paleozoic	Igneous	Dalhousie Granite	---	Micaceous Granite
-----Unconformity-----				
Late Proterozoic	Sedimentary	Manjir formation	---	Grey and purple para-conglomerates with some intercalated bands of grey slates. Few quartzites bands in the lower part in some sections.
Middle to upper Proterozoic	Sedimentary	Chamba formation	---	Monotonous alternations of meta greywacke and slate forming shalyflysch.
	Metamorphic	Pindru formation	---	Greyish green, sometimes talcosephyllites and schists, garnetiferousbiotite schist, micaceousquartzites and interbedded with some bands of dark grey crystalline limestone, with associated Dalhousie granite.
	Metamorphic	Khokan formation	---	Chlorite Mica Schists, Slate and Quartzite
	Metamorphic	Ghar Formation	---	Para-gneisses
-----Main Central Thrust (MCT)-----				
Lower Proterozoic	Igneous	Mandi formation	Darla volcanic rocks	Basaltic and andesitic flows
-----Main Boundary Fault (MBT)-----				

MATERIALS AND METHODOLOGY

Data Source

Selection of the rightful elements with their assistance in the landslide occurrences is necessary (Ayalew and Yamagishi 2005). Varnes 1984, representation of all factors responsible for slope failures must be required for hazard zonation of landslides. Stability of slopes was influenced by the surface topography than the geomorphology of the terrain (Dai and Lee 2002). The researchers (Varnes 1984; Kanungo et al. 2009) suggested that factors like: slope, aspect, curvature, relative relief, soil, Land use and land cover (LULC), lithology, geomorphology, rainfall, drainage density, and lineament density are the main contributors of the slope failures in Himalayan terrain. LULC and inventory of landslides were generated through the LISS IV satellite imagery and Google Earth images. Validation of the identified landslides and land cover was done through various field visits. Relative relief, slope gradient, slope aspect, and curvature were generated through the 3D PAN Satellite imagery of CartoSat -1D with

resolution of 30m. Subsidiary data like drainage was developed from Survey of India 1986 topographic sheets (1:50,000), lithological and lineament map from Keshar Singh and V. C. Thakur 1989, Keshar Singh 2011 and 1993. The rainfall record from January 2000 to February 2019 was collected from Indian meteorological center Shimla. Other maps were generated from data provided by the concerned governmental and non-governmental agencies (Table 2). Figure 3 shows all the landslide causative factor maps which were correlated with the mass movements of the slopes.

Table 2: Data Type/Source for LHZ Mapping

Sr. No.	DATA TYPE	DESCRIPTION	SOURCE	PURPOSE
1	Topographical Map	1:50,000	Survey of India	DEM: Relative Relief, Slope, Aspect, Drainage network and Density
2	Satellite Data Cartosat DEM	Spatial Resolution 1m	National Remote Sensing Centre (NRSC), Hyderabad, India	Land use and land cover
	IRS-P6 LISS- III	Spatial Resolution 23.5m		
3	Geological and Limeament Map	Scale 1:50,000	Geological Survey of India and articles of Keshar Singh 2011 and 1993 Keshar Singh and V. C. Thakur 1989	Geology, Lineament Density
4	Geomorphology	Scale 1:50,000	Bhuvan, National Remote Sensing Centre (NRSC), Hyderabad, India	Geomorphology
5	Soil Map	Scale 1:50,000	Survey of India	Soil
6	Field Data	GPS Locations	-	Landslide Inventory
7	Rainfall Data	Scale 1:50,000	Indian Metrological Centre, Shimla, H.P., India	Rainfall Map

Figure 3: Flow chart for landslide hazard zonation mapping

(a) Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process technique was utilized by various researchers for landslide hazard zonation. The AHP technique is useful in evaluation of different parameters role in slope failure (Varnes 1990 and 1980, Satty 2005, Feizizadeh and Blaschke 2012). It is based on three principles: decomposition, comparative judgment and synthesis of priorities (Pandey et al. 2016, Singh and Sarda 2018).

Weight of each class of landslide causative factor is analyzed using AHP approach through the comparison of each pair in the form of pairwise comparison matrix. Weights were assigned in the scale of 1-9 (equal importance 1, moderate importance 3, strong importance 5, very strong importance 7 and extremely importance as 9) on the basis of importance of each factor in triggering the failure of the slopes. Results of inverse comparison are reciprocal (1/2 to 1/9) for the given weight to mandatory triggering element. Consistency of each matrix was validated through the consistency ratio (Satty 1990, 1994) which is analyzed for each factor from the weights of each element through equation 1 and 2.

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}} \quad 1$$

$$\text{Consistency Index (CI)} = \frac{\lambda_{\max} - n}{n - 1} \quad 2$$

Where, order of matrix as 'n' and ' $\lambda_{\max}$ ' denoted as matrix principle eigen value and Random index values were used from table 3.

Table 4: Random Index values for different matrix orders (N)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

Weight values assigned for the different factors on their importance in the form of matrix are shown in Table 3. Reciprocal weight values were given for inverse comparison of factors based on dominant causative factor. CR value less than 0.1 indicates reasonable consistency level of weight values (Satty and Vergas 2000). Finally to analyze landslide hazard index (LHI) values, all weights were combined by using equation 3.

$$LHI = \sum_{j=1}^n W_k \times W_{ik} \quad 3$$

Where, LHI = landslide hazard index values; W_{ik} =weight of subclass *i* in factor *k*; W_i = weight of the factor *k*; *n* = total number of factors.

(b) Information value model

Based on assumption factors responsible for slope failures in past was the same that will cause landslides in future. Distributions of landslides based on their location, size and type were compared with each causative factor for assigning the weight values. Assignments of weight values were depend upon the density of landslides in each class of the factor (Lin and Tung 2003). Information value model (IVM), weight of evidence (WOE), frequency ratio (FR) and weighted overlay etc. statistical methods were used for the analysis of weights values. Van Westen 1993 modified the information value model proposed by Yin and Yan 1988. Researcher has used information value model for landslide hazard zonation mapping in such study. Rainfall, slope gradient, slope aspect, geology, drainage density, lineament density, geomorphology, relative relief, land use/cover soil and curvature factors plays very important role in failures of slopes. This method aims to find the probability of a landslide event based on the comprehensive information available of the significant factors by using equation 4.

$$l(Lx_i) = \ln \frac{Npix(Si)/Npix(Ni)}{\sum Npix(Si)/\sum Npix(Ni)} \quad 4$$

Where, factor of class information value $l(Lx_i)$, number of landslide pixels in each class $Npix(Si)$, total number of pixels in each class $Npix(Ni)$, sum of landslide pixels in the study area $\sum Npix(Si)$, sum of total pixels in the study area $\sum Npix(Ni)$. Equation 5 analyzes the landslide hazard index values through summing of all weight values.

$$LHI = \sum_{i=1}^n l(Lx_i) = \sum_{i=1}^n \frac{Npix(Si)/Npix(Ni)}{\sum Npix(Si)/\sum Npix(Ni)} \quad 5$$

Where LHI indicates the landslide hazard index values, *n* denotes the total number of factors. $LSI < 0$ indicates the less than likelihood average, $LSI = 0$ indicates the landslide likelihood equal to the average, $LSI > 0$ indicates the average of landslides.

Thematic Layers

(a) Landslide Inventory

Interpretation of satellite images, past landslide records from different agencies and field surveys play significant role in the development of landslide inventory (Kayastha et al. 2013). In the present study, inventory of 184 landslides was developed by collecting data from the past records of border road organization (BRO), public works department (PWD), National Highway Authority of India (NHAI) and LISS IV satellite images and Google earth images which were validated through field visits and updated to present day status (Figure 4a). The cause of maximum numbers of landslides (debris and rock falls) are correlated with thrusts and lineaments. Rock fall near Chowari town and 20 km before Chamba town weretriggered by the seismic shocks and rainfall (Fig 1b and f), debris flow at 500m from Lahru town and Banikhet landslides took place due to heavy rainfall which is triggering factor for 75% of the total landslides in the area.

(b) Lithology

Lithology holds an important role in the stability of the mass movements, in minimizing the erosions and in weathering of rocks as well (Anabalgan 1992). Upper Shiwalik, Pindru, Mandi, Khokan, Khalel (Lilang group), Ghar, Dharmasala and Chamba formation, Dalhousie granite with alluvium rock bodies and their sequence of succession has been presented in Figure 4(b) and Table 2. Lithology map for the study was developed from the articles of Keshar Singh 2011 and 1993 Keshar Singh and V. C. Thakur 1989.

(c) Land use and land cover

Contribution of land use/ cover in slope failures has been reported well in literature by several researchers(Lee et al. 2013). Landslide prone areas are the evidences of land use changes like road expansions, new construction activities (homes, bridges and reservoirs), deforestation and rapid expansion in agriculture fields (Jaiswal et al. 2010). Comparison of past data (SOI topographic sheets(43P14, 43P15, 52D2 and 52D3)) with the present data (Google earth, LISS IV satellite imageries) has been employed in the preparation of LULC map through digitization and change detection tool as presented in Figure 4(c). Forest, sparse vegetation and agriculture classes of the region have been found to cover 79.63% while water bodies and snow occupied only 1.08% area.

(d) Soil

Five types of soils were found in the study area like loamy skeletal soil with loamy surface, rocky outcrops, coarse loamy, loamy and sandy skeletal soils (Figure 4d). Coarse loamy soil covered a minimum area of 3.49% while 35.47% maximum area was found to be covered with loamy skeletal soil. Landslides were found to be more prone in sandy skeletal soil.

(e) Drainage Density

Drainage density plays an important role in the weathering and soil erosion on the slopes(Demir et al. 2013). Orientation of lineaments was followed by the stream networks in region. Density of stream networks depends upon the ground water conditions (Kavzoglu et al. 2014). Stream networks were extracted from satellite imagery of Cartosat -1D sensor by using hydrology tool of spatial analyst in ESRI (Arc GIS) software and digitization of survey of India topographic sheets at the scale of 1:50,000. Drainage density map was developed by using equation 6 and reclassified into four classes (Very low, low, moderate and high drainage density) Figure 4(e).

$$\text{Drainage Density} = \frac{\text{Total Stream Length}}{\text{Total Drainage Area}} = \frac{\sum_{i=1}^n L}{\sum A} \quad 6$$

Figure 3:Thematic data layers (a) Landslide inventory map, (b)Lithology map, (c) Land use and cover map (d) Drainage density(e) Lineament Density map (f) Lineament density map.

(f) Lineament Density

Role of rock cleavages, joints and fault planes are very important for controlling pore pressure (Ramakrishnan et al. 2013). Intense shearing of rocks is directly affected by the active fault planes which leads rock masses of mountains towards failures (Leir et al. 2004). Lineament density map was prepared from the various literatures and maps at the scale of 1:50,000, National remote sensing center (NRSC), Indian space research organization (ISRO). Lineament density map has been classified into three classes viz. low, moderate and high density based on equation 7 (Figure 4f).

$$\text{Lineament Density} = \frac{\text{Total Lineament Length}}{\text{Total Lineament Area}} = \frac{\sum L}{\sum A}$$

(g) *Slope Gradient*

Slope value is calculated on the basis of change in altitude. Slope degree plays vital role for controlling slope stability (Lee and Min 2001). Figure 4(g) shows the reclassification of slope map into five subclasses (Normal slope 0-15°, Low 15°-30°, Moderate 30°-45°, Steep 45°-60°, Very steep 60°-80°).

(h) *Geomorphology*

The geomorphology map of the study area was delineated at the scale of 1:50,000 based on the Landsat, Cartosat 1D and Google earth images. Structural, Denudational, low and moderate dissected hills were identified and validated through field visits. River and flood plains of river covers only 4.56% of the area while 95.44% of area is covered by the structural and denudational hills as shown in Figure 4h.

(i) *Slope Aspect*

The aspect of a slope is known as direction of the slope facet with respect to north. Aspect of slopes depends upon the dryness of air, soil moisture and solar heat effect (Yalcin 2008). The slope aspect map was classified into eight classes viz. north, north east, east, south east, south, south west, west and north west as mentioned in Figure 4i.

(j) *Rainfall*

Rainfall is an important causative factor in the occurrences of slope failures. Rainfall data of different metrological stations in the region was collected and analyzed from January 2000 to February 2019. Lowest rainfall record is 1437mm in year 2002 and maximum rainfall 1691mm in year 2017 was recorded in region. Kriging tool of GIS is used for development of rainfall map. Rainfall map of the study area was reclassified into four class's viz. 1437-1547mm, 1548-1627mm, 1628-1691mm, and 1692-1752mm as shown in Figure 4(j).

(k) *Relative Relief*

Slopes angles and direction of slopes depend upon altitude range of the area. Altitude of Lahru town is 656m and Kalatopis 2757m from mean sea level. Relative relief map was developed from the contour map which digitized from SOI topographic sheets at the scale of 1:50,000. Reclassify tool of GIS has been used for reclassification of relative relief map into four classes (656-1190m, 1191-1581m, 1582-2041m, 2042-2757m) on the basis of slope failure occurrences, type and size in relative reliefs (Figure 4k).

(l) *Curvature*

Curvature is the intersection of random planes with surface (Ramesh and Anbazhagan 2015). Frictional and cohesion forces act differently in different types of surfaces. Inflow and outflow of water or drainage systems is controlled by these surfaces. Flat, Convex and Concave surfaces are normally found in hilly terrain which plays important role in erosion and weathering processes of slopes. Curvature map was developed from the digital elevation model (DEM) of the region (1:50,000) and classified into three classes (Flat, Convex and Concave) Figure 4(l).

Results and Discussion

(a) *Landslide hazard zonation using analytical hierarchy process (AHP) method*

Landslide hazard zonation maps are prepared with impact from different causative factor maps on the scale of 1:10,000 in GIS environment. Digital elevation model of study area is obtained after the conversion of vector data (point, line and polygon) into raster data and reclassification of all factors (pixels 10 x 10m) have been done. The weight values of factors are obtained through analysis of raster data model by using pair wise comparison matrix. Raster data model helps in the analysis of landslide hazard index (LHI) values for development of landslide hazard zonation maps (Figure 5a). Landslide hazard index (LHI) values were analyzed through multiplication of subclass weightage of factors to the factor weightage based on equation 8.

Weight values of analytical hierarchy process (AHP) are shown in table 4 after normalization of all subclasses of causative factors. Ratio of all subclass causative factors average values and total number of subclass in each factor are used for the normalization of all AHP weight values. Excel sheets are used for analysis of consistency index values and table 4 helps in calculation of random index values. Slope gradient is one of the important causative factor which is responsible for landslide incidences. AHP weight values in the case of steeper slopes between 60°-80° has high values of 0.527 followed by lesser slopes while lowest slope angle between 0-15° have lesser AHP weight values of 0.048. Slopes of hills facing in the direction of north west (conglomerate boulders) 0.362 and south

318 west (sandstones) 0.233 have high AHP weight values while slopes which facing south and east directions have less
 319 AHP weight value

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Figure 4 (Continued...):Thematic data layers (g) Slope gradient map, (h) Geomorphology map, (i) Aspect map (j) Rainfall map (k) Relative relief map (l) Curvature map.

Conditions of landslide hazards is also affected by density of drainage networks and lineaments. In the study area very low and low classes of lineament (0.080, 0.77) and drainage density (0.067, 0.076) have less impact on landslide incidences respectively. High density of lineament (0.618) and drainage networks (0.608) have high impact followed by moderate class of both factors (0.226 and 0.216). In the case of relative relief, high altitude (2042-2757m) of terrain is highly effected by landslide resulted high AHP value of 0.606 followed by less (1582-2041m) altitude of terrains with less number of landslides (0.229) while 656-1190m of altitude have average of least number of landslides with AHP value 0.054. Geomorphology of the terrain classified into six categories in which low dissected structural hills (0.326) are most effected by slope failures due to exposure for weathering processes

followed by moderately dissected denudation hills (0.31) and moderate dissected structural hills (0.199). Land covered by shrub have high AHP value (0.235) followed by road (0.183) and settlement (0.134) while other classes of LULC have less AHP values. Moisture containment play very important role in formation of slope curvatures. Flat type of slope surfaces have lesser AHP value of 0.083 other than concave (0.723) and convex (0.194) curvature type of land surfaces. Rainfall in the study area given the 0.606, 0.216, 0.091 and 0.042 AHP values for 1692-1752mm, 1628-1691mm, 1548-1627mm and 1437-1547mm classes respectively. Conglomerate boulders of upper Siwalik formation (0.315) most affected areas of the study area which followed by sandstones with shale of Dharamsala formation (0.153) while clay boulders and sand of alluvium formation (0.026), slate, phyllite, carbonaceous and quartzite of Chamba formation (0.022) and micaceous granite of Dalhousie formation have least AHP values. Among all the factors soil is important factor for incidences of slope failures. The outcome of all subclasses comparison of soil, coarse loamy soil have highest AHP value of 0.545 followed by loamy skeletal soil 0.162. Equation 5 was used for the delineation of landslide hazard index values, very low (2.95%), low (4.27%), moderate (24.40%), high (31.03%) and very high (40.30%) classes of landslide hazard zones were obtained respectively from classification of landslide hazard index values by using natural break system. AHP based LHZ map was delineated by modest form of the landslide hazard index equation 5 in GIS environment which can be written as:

$$LHI_{AHP} = (SG_{AHP} \times 0.09) + (AG_{AHP} \times 0.07) + (LC_{AHP} \times 0.08) + (Geom_{AHP} \times 0.08) + (RR_{AHP} \times 0.018) + (Soil_{AHP} \times 0.08) + (Lith_{AHP} \times 0.07) + (LD_{AHP} \times 0.012) + (DD_{AHP} \times 0.018) + (Rain_{AHP} \times 0.012) + (Curv_{AHP} \times 0.02)$$

Landslide hazard index (LHI) values were determined through AHP model between 0.03748 -0.30000. Maximum area of very high, high and moderate hazard zones of landslides are prevailing in south east (Lahru, Banikhet and Dalhousie) and south west (Lahru) direction of selected examined area of Chamba district while very low and low hazard zones lies near Chamba city in north direction of the study area. Mostly very high and high hazard zones lies near lineament density high and exposed land cover for erosion and weathering processes while very low and low hazard zones are located near water bodies, densely vegetated covered and flood plains. It can be clearly observed that 71.33% of high and very high hazard zones are covered while moderate 24.40%, low 4.27% and very low 2.95% hazard zones are covered respectively (Figure 4c). Density of landslides also increases while frequency of landslides has increased. Consistency index (CI) values are calculated for the weight values accuracy of all factors subclass through the MS excel sheet and random index values obtained from table 3. Consistency ratio (CR) value 0.074 is obtained for the weight value of prevailing factor for pair through pairwise comparison (equation 2).

Table 4: Analysis of thematic layers and subclasses causative factor

Factors	1	2	3	4	5	6	7	8	9	10	11	Normalized Weight (W _{ik})
Slope Gradient (°)	1	5	1	0.5	2	0.14	0.11	1	0.14	5	3	0.062
Aspect Gradient	0.2	1	0.25	0.25	0.5	0.2	0.2	0.14	0.2	1	1	0.024
Soil	1	4	1	0.5	3	0.2	0.2	0.33	0.17	2	2	0.052
Lithology	2	4	2	1	2	0.33	0.5	1	0.2	5	2	0.078
Geomorphology	0.5	2	0.33	0.5	1	0.5	0.14	1	0.14	5	2	0.049
LULC	7	5	5	3	2	1	0.5	3	0.5	5	2	0.149
Rainfall	9	5	5	2	7	2	1	3	1	9	7	0.222
Lineament Density	1	7	3	1	1	0.33	0.33	1	1	4	5	0.101
Drainage Density	7	5	6	5	7	2	1	1	1	6	5	0.211
Relative Relief	0.2	1	0.5	0.2	0.2	0.2	0.11	0.25	0.17	1	0.33	0.02
Curvature	0.33	1	0.5	0.5	0.5	0.5	0.14	0.2	0.2	3	1	0.033
Consistency Ratio	0.074											
Comparison of factor classes												
Slope Gradient (°)												W _{ik}
0-15	1											0.048
15-30	1	1										0.052
30-45	3	2	1									0.124
45-60	5	5	2	1								0.249
60-80	7	7	7	3	1							0.527
Consistency Ratio	0.09											
Aspect Gradient												
North East	1											0.115

East	0.33	1											0.044
South East	1	5	1										0.109
South	0.33	1	0.33	1									0.042
South West	5	5	2	5	1								0.233
West	0.25	1	1	1	0.2	1							0.05
North West	7	5	7	7	2	5	1						0.362
North	0.25	1	0.33	1	0.2	1	0.2	1					0.045
Consistency Ratio	0.07												
Land Cover													
Sparse Vegetation	1												0.033
Settlement	5	1											0.134
Forest	0.33	0.2	1										0.024
Agriculture Land	5	0.5	3	1									0.077
Shrub	5	4	6	2	1								0.235
Rocky Terrain	7	0.33	3	1	0.25	1							0.107
Road	9	2	5	5	0.5	1	1						0.183
Khazaiar Lake	1	0.25	5	1	0.33	0.25	0.25	1					0.056
River	2	0.2	2	0.5	0.2	0.33	0.2	1	1				0.040
Consistency Ratio	0.08												
Geomorphology													
Structural Hills - Moderately (SHM) Dissected	1												0.199
Structural Hills- Low Dissected	2	1											0.326
Denudational Hills – Moderately Dissected (DHM)	2	1	1										0.31
River	0.17	0.2	0.25	1									0.056
Flood Plain	0.2	0.14	0.2	1	1								0.051
Valley Fill	0.33	0.17	0.14	1	1	1							0.058
Consistency Ratio	0.08												
Relative Relief													
656-1190	1												0.054
1191-1581	3	1											0.112
1582-2041	5	4	1										0.229
2042-2757	7	5	7	1									0.606
Consistency Ratio	0.018												
Soil													
Sandy skeletal soil	1												0.147
Loamy skeletal soil	2	1											0.162
Loamy skeletal soil with loamy surface	0.14	0.2	1										0.03
Loamy soil	0.5	0.33	3	1									0.076
Calcareous loamy soil	5	9	9	9	1								0.545
Rocky outcrops	0.2	0.2	2	0.3	0.11	1							0.041
Consistency Ratio	0.08												
Lithology													
Alluvium (Clay boulder and sand)	1												0.026
Chamba formation (Slate, carbonaceous	1	1											0.022

phyllite and quartzite)												
Dalhousie Granite (Micaceousgranite)	1	1	1									0.021
Dharmsalaformation (Sandstone with shale)	3	7	7	1								0.153
Ghar formation (Paragneisses)	5	5	3	0.2	1							0.056
Khalelformation (Lilang Group- Limestone with calcareous shale and ferruginous chert)	5	3	5	1	5	1						0.106
Khokanformation (Chlorite, mica schist, slate and quartzite)	7	5	7	0.5	3	1	1					0.105
Mandiformation (Mandivolcanoes)	7	7	5	0.33	5	1	1	1				0.109
Pindruformation (Interstratified schist’s and quartzite)	1	5	7	0.2	3	0.33	0.33	0.33	1			0.065
River	1	1	1	0.2	0.2	0.2	0.2	0.2	0.2	1		0.022
Upper Siwaliks(Boulder Conglomerate)	7	7	7	2	7	7	7	7	7	7	1	0.315
Consistency Ratio	0.07											
Lineament Density												
Very low	1											0.080
Low	2	1										0.077
Moderate	3	3	1									0.226
High	7	8	3	1								0.618
Consistency Ratio	0.012											
Drainage Density												
Very low	1											0.067
Low	2	1										0.076
Moderate	4	3	1									0.216
High	9	7	4	1								0.643
Rainfall												
1437-1547	1											0.042
1548-1627	3	1										0.091
1628-1691	8	3	1									0.261
1692-1752	9	9	3	1								0.606
Consistency Ratio	0.012											
Curvature												
Flat	1											0.083
Convex	3	1										0.194
Concave	7	5	1									0.723
Consistency Ratio	0.02											

(b) *Landslide hazard zonation using information value method*

Analysis of correlation between slope failure locations and thematic layers (slope gradient, slope aspect, lithology, lineament density, geomorphology, drainage density, rainfall, soil, land use/ cover, relative relief and curvature) were executed through combine tool in GIS environment for information value method. Landslide hazard zonation map has been delineated based on equation 9 with the help of map algebra tool and raster calculator.

$$LHI_{Inf} = SG_{Inf} + SA_{Inf} + RR_{Inf} + Lith_{Inf} + Soil_{Inf} + LU_{Inf} + DD_{Inf} + LD_{Inf} + Rain_{Inf} + Geom_{Inf} + Curv_{Inf} \quad 9$$

Table 5: Spatial relationship between each factor causing landslide and landslide using the information value model

Factors	Class	N _{CL_Pix}	N _{SL_Pix}	Conditional Probability (C _p)	Priority Probability (P _p)	C _p /P _p	Information Weight Value (IVM)
Slope	0-15	597082	0	0	0.001444	0	0
	15-30	519151	764	0.001472	0.001444	1.02	0.008
	30-45	608521	918	0.001509	0.001444	1.05	0.019
	45-60	638257	1039	0.001628	0.001444	1.13	0.052
	60-80	372536	1229	0.003299	0.001444	2.28	0.359
Aspect Gradient	North east	263230	414	0.001573	0.001444	1.08	0.037
	East	79738	24	0.000301	0.001444	0.21	-0.681
	South east	364840	768	0.002105	0.001444	1.46	0.164
	South	322945	55	0.00017	0.001444	0.12	-0.928
	South west	337057	1333	0.003955	0.001444	2.74	0.437
	West	335608	7	0.0000209	0.001444	0.014	-1.84
	North west	369205	1302	0.003526	0.001444	2.44	0.388
	North	662924	47	0.0000709	0.001444	0.05	-1.309
Lithology	Alluvium (Clay boulder and sand)	95316	0	0	0.001444	0	0
	Chamba formation (Slate, phyllite, carbonaceous and quartzite)	9769	0	0	0.001444	0	0
	Dalhousie granite (Micaceous granite)	75902	0	0	0.001444	0	0
	Dharmasala formation (Sandstone with shale)	177997	574	0.003225	0.001444	2.23	0.349
	Gharformation (Paragneisses)	326207	14	0.0000429	0.001444	0.02	-1.527
	Khalel formation (Lilang group- limestone with calcareous shale and ferruginous chert)	30528	62	0.002031	0.001444	1.4	0.148
	Khokan formation (Chlorite, mica schist, slate and quartzite)	767634	200	0.000261	0.001444	0.18	-0.744
	Mandi formation (Mandi volcanoes)	342393	676	0.001974	0.001444	1.37	0.136
	Pindru formation (Interstratified schists and quartzite)	829363	376	0.000453	0.001444	0.31	-0.503
	River	19345	17	0.000879	0.001444	0.6	-0.216
	Upper Siwaliks (Boulder conglomerate)	61093	2031	0.033244	0.001444	23.02	1.362
	Low	254298	409	0.001608	0.001444	0.9	-0.047
	Moderate	783874	1199	0.00153	0.001444	0.94	-0.025
Drainage Density	High	830755	1848	0.002224	0.001444	0.65	-0.188
	Very High	866620	494	0.00057	0.001444	2.53	0.404
Geomorphology	Structural hills- moderately dissected (SHM)	935614	438	0.000468	0.001444	0.32	-0.489
	Structural hills- low dissected	61221	2049	0.033469	0.001444	23.18	1.365
	Denudational hills- moderately dissected (DHM)	1613900	1463	0.000906	0.001444	0.63	-0.202
	River	19473	0	0	0.001444	0	0

	Flood plain	95444	0	0	0.001444	0	0
	Valley fill	9895	0	0	0.001444	0	0
Lineament Density	Very low	266883	1350	0.005058	0.001444	0.29	-0.545
	Low	711703	1471	0.002067	0.001444	0.7	-0.156
	Moderate	999906	621	0.000621	0.001444	2.32	0.366
	High	757055	508	0.000671	0.001444	2.15	0.333
Soil	Loamy skeletal soil with loamy surface	488350	51	0.000104	0.001444	0.07	-1.141
	Loamy skeletal soil	970307	443	0.000457	0.001444	0.32	-0.5
	Rocky outcrops	131122	0	0	0.001444	0	0
	Loamy soil	508273	235	0.000462	0.001444	0.32	-0.495
	Sandy skeletal soil	542058	3221	0.005942	0.001444	4.11	0.614
	Coarse loamy soil	95437	0	0	0.001444	0	0
Land Use/ Cover	River	26971	0	0	0.001444	0	0
	Sparse vegetation	376062	1004	0.00267	0.001444	1.85	0.266
	Settlement	92669	1178	0.012712	0.001444	8.8	0.945
	Forest	1266924	84	6.63E-05	0.001444	0.04	-1.338
	Agriculture land	535376	724	0.001352	0.001444	0.94	-0.028
	Shrub	269982	549	0.002033	0.001444	1.41	0.149
	Rocky terrain	148181	327	0.002207	0.001444	1.53	0.184
	Road	19174	84	0.004381	0.001444	3.03	0.482
Rainfall	Khajiar Lake	208	0	0	0.001444	0	0
	1437-1547	89859	582	0.006477	0.001444	0.22	-0.652
	1548-1627	629317	1527	0.002426	0.001444	0.6	-0.225
	1628-1691	951594	347	0.000365	0.001444	3.96	0.598
Relative Relief	1692-1752	1064777	1494	0.001403	0.001444	1.03	0.012
	656-1190	681747	1186	0.00174	0.001444	0.83	-0.08
	1190-1581	868767	1760	0.002026	0.001444	0.71	-0.147
	1581-2041	696372	537	0.000771	0.001444	1.87	0.272
Curvature	2041-2757	488661	467	0.000956	0.001444	1.51	0.179
	Flat	152199	0	0	0.001444	0	0
	Convex	1283651	1094	0.000852	0.001444	0.59	-0.229
	Concave	1299697	2856	0.002197	0.001444	1.52	0.182

Weight value of slope gradient classes demonstrates the increasing order of weights from 15° to 80° where, 0.359 weight for 60° to 80° slope is highest weight value followed by 0.052 (45° to 60°), 0.019 (30°-45°) and 0.008 (15°-30°) whereas no landslide was found between the slope angle 0 to 15° due to flat terrain and river beds. Observation of these weight values clearly shown that number of landslides increased where slope of terrain is high and numbers of landslides are decreased such as slope angle of terrain decreases. The weight of unattached sections of strata and gravity actions were more prominent on inclined slopes in contrast to moderate slopes, but failure of slopes depends upon the strength of shear forces of material, shear strength on inclined slopes are less than moderate slopes resulting inclined slopes are fails early than moderate slopes. In case of slope aspect, the South West (0.437) and North West (0.388) direction facing slopes are the frequently effected by landslides whereas least number of landslides were recorded in the north (-1.309) and west (-1.840) classes of slope aspect due to monsoon follows mostly in north west and south west directions of the region and these regions are exposed for the weathering processes from rainfall and wind. Relative relief of the terrain also play very important role in landslide occurrences, high number of slope displacements are recorded (0.272) in 1581-204m and followed by 2041-2757m (0.179) while number of slope displacements are recorded in 656-1190m (-0.080) and 1190-1581 (-0.147). In terms of the curvature, flatter surface have zero weight values due to absence of slope and convex slope experienced less weight values (-0.229) due to less number of slope failure incidences while concave slopes are experienced high weight values (0.182) due to high number of slope failure incidences shown in table 5.

In the region where landside frequency high, density of drainage networks would also high (0.333) while where landside frequency very low (-0.545), density of drainage networks would also low. Tributaries and gullies of main rivers are contributed in toe cutting of slopes and bank erosion. Lineaments play an important role for initiating landslides. Planar and toppling such types of slope failures are managed by different types of lineaments such as fault, joint etc. Initiation of landslides are commonly affected by strength and orientation of discontinuities, greater information values were evaluated for high (-0.188) and very high lineament density class (0.404). In case of soil

map, sandy skeletal soil (0.614) has evidence of maximum number of landslide which was followed by loamy skeletal soil (-0.50). Zero weight value was obtained for rocky outcrops and coarse loamy soil classes due to absence of landslides. Sandy skeletal soil has maximum exposed for weathering process due to river and gullies. Among all factors lithology terrain play very important role. Mainly igneous (Micaceous Granite, Mandi Volcanes- Basaltic and andesitic flows) sedimentary (sandstones, clay, sandstone with shale, limestone with calcareous shale and ferruginous chert, conglomerate boulder) and metamorphic (Slate, Phyllite, Carbonaceous and Quartzite, Paragneisses, Chlorite, Mica Schist, Slate and Quartzite, Interstratified Schists and Quartzite) rocks were found into various formations like Alluvium, Upper Siwalik, Pindru, Mandi, Khokan, Khalel (Lilang group), Ghar, Dharmasala, Chamba and Dalhousie. There are none evidence of slope failure into Chamba and Dalhousie formation while into upper Siwalik rock formation has high number of slope failures resulted high weight value of 1.362 followed by Khalel and Mandi rock formations. Geomorphology of terrain classified into six various classes like structural hills-moderately dissected (SHM), structural hills- low dissected, and denudational hills - moderately dissected (DHM), river, flood plains and valley fills. Weight values of low dissected structural hills are analyzed high weight value of 0.326 which followed by moderately dissected denudational (0.32) and structural hills (0.199) while river, flood plain and valley fills are zero weight value due to none presence of landslides. In the case of land use and cover, forest (-1.338) and agriculture lands (-0.028) of region have negative value while slopes which correlated with settlement areas have high weight value 0.945. Road networks (0.482), sparse vegetation (0.266), rocky terrain (0.184) and shrub (0.149) have also follow the same trend of information weight values. Among all variables rainfall is most important and essential factor which recorded by Indian metrological department from 1437mm to 1752 mm. low regions of rainfall 1437-1547mm (-0.652) and 1548-1627mm (-0.225) have less weight values while high regions of rainfall 1628-1691mm has high weight value of 0.598 which followed by 1692-1752mm (0.012).

Figure 5: Landslide hazard zonation maps using AHP and Information value methods: (a) Analytical hierarchy process (AHP) hazard map (b) Information value (Inf.V) hazard map

Finally to develop landslide hazard zonation of the region, landslide hazard index values are analyzed from summation of all information weight values by equation 9. Landslide hazard index values were classified into very low (1.2%), low (5.31%), moderate (20.03%), high (29.26%) and very high (44.2%) by using reclassify tool of GIS.

Figure 5 (continued...):(c) Landslide area percentage graph in each landslide hazard zone

VALIDATION

Very high and high hazard zones were discovered with various types of landslides likely debris flow, rock fall, rock slides and earthy flow in the region. Several researchers suggested that density of landslide in each landslide hazard zone is essential tool for validation of hazard zonation maps (Sarkar and Kanungo 2004). Figure 4(c) shows the comparison of landslide hazard zone classes by AHP and Information value method on the basis of area covered by landslides in each hazard zone. Dissimilarity was observed between the hazard classes of both landslide hazard maps (information value method and AHP). Very low hazard zone occupied 2.95% and 1.2% areas in case of AHP and information value method with landslide density (Figure 5c).

Several researchers have proposed the success rate curve method for comparative analysis and validation of hazard maps through analysis of area under curve (Chung and Fabbri 2003; Guzetti et al. 2006; Frattini et al. 2010), the same has been utilized in present study. The LHZ maps were reclassified into 100 classes using reclassify tool of natural break method in GIS environment for the validation. Pixels of landslides in each class of hazard map were obtained by combining the landslide inventory raster dataset with the hazard zonation map. Landslide area percentage helps into the analysis of the area under curve, cumulative sum and accuracy of landslides (Figure 6). The success rate for AHP based LHZ map has been calculated as 78.62% while for information value based LHZ map, it is 85.17% which is more accurate.

Figure 6: Successive rate curve method for validation of both AHP and Inf.V methods

CONCLUSION

Himalayan region of India is prominent evidence of most disastrous natural hazards like landslides. Assessment of landslide hazard is essential for Chamba district, Himachal Pradesh, India before any construction such as road (SH-28, NH-154A and link road), reservoirs etc. In the present study, AHP and IV methods were utilized to accomplish hazard zonation of landslides along study area (Lahru to Chamba, Chamba district, Himachal Pradesh). Inventory of different types of landslides were produced from the various sets of data to achieve the objectives of the study. A total of 184 landslides were identified from these data sources. Total eleven various factors (slope gradient,

slope aspect, relative relief, curvature, lithology, drainage density, lineament density, soil, land use land cover, geomorphology, and rainfall) were identified which play crucial role in the occurrences of slope failures and they were analyzed through AHP and information value method. Weights for each factor class were attributed during the process of modeling. The landslide density as well as success rate curve method was adopted for the validation of the LHZ maps. Density of landslides were increasing in each landslide hazard zone, 6.55% high prediction rate of information value approach (85.17%) is higher than AHP process (78.62%) therefore hazard map of landslides obtained from the information value is more accurate than the hazard map of landslides from the AHP.

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ABBREVIATION

GIS	Geographical Information System
NH	National Highway
SH	State Highway
LULC	Land Use/ Cover
LHEF	Landslide Hazard evaluation Factor
BIS	Bureau of Indian Standard
IMD	Indian meteorological department
VT	Vaikrita Thrust
MCT	Main Central Thrust
MBT	Main Boundary Thrust
LISS	Linear Imaging Self-Scanning sensor
NRSC	National Remote Sensing Centre
Inf. V	Information Value Method
AHP	Analytical Hierarchy Process
LHI	Landslide Hazard Index
LHZ	Landslide Hazard Zonation
SRC	Successive Rate Curve

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Figures

Figure 1

Photographs of critical slopes taken during March 2019 field visit along SH28 and NH -154A (a) Earth debris failure 500m from Lahru at SH28 (b) Transitional and Rock debris landslide near Chowari at SH28, (c) Debris flow landslide neat Jot at SH28 (d) Rock fall and Earth flow landslide 250m before Ghatasani bridge at NH145-A (e) Earth Debris flow landslide near Banikhet at NH-154A (f) Rock fall landslide near Chamba at NH154A.

Figure 2

Study area Lahru to Chamba, Chamba District, and Himachal Pradesh, India

Figure 3

(Manuscript Figure 3.1) Flow chart for landslide hazard zonation mapping

Figure 4

(Manuscript Figure 3.2-Figure 4) Thematic data layers (a) Landslide inventory map, (b) Lithology map, (c) Land use and cover map (d) Drainage density (e) Lineament Density map (f) Lineament density map. (g) Slope gradient map, (h) Geomorphology map, (i) Aspect map (j) Rainfall map (k) Relative relief map (l) Curvature map.

Figure 5

Landslide hazard zonation maps using AHP and Information value methods: (a) Analytical hierarchy process (AHP) hazard map (b) Information value (Inf.V) hazard map. (c) Landslide area percentage graph in each landslide hazard zone

Figure 6

Successive rate curve method for validation of both AHP and Inf.V methods