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Snow avalanche based susceptibility assessment of selected districts in northern zone of Pakistan applying MCDA approach in GIS

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Abstract

Snow avalanche is considered a critical natural hazard that actively occurs globally in snow-covered mountainous terrain. These physical phenomena have adversely affected the natural system and human lives due to variations and complexness in occurrence. The data and information about its probability are mostly lacking and inaccessible in complex terrains. The present study is an attempt to determine avalanche susceptibility of the selected districts in the northern areas of Pakistan using multi-criteria decision analysis (MCDA) approach in a GIS environment. The critical topographic factors; elevation, slope, aspect, plan curvature, and profile curvature as avalanche causation parameters are incorporated as local functions in MCDA model. Available high-resolution digital elevation model (SRTM 30 m) was used to generate considered factors. The final spatial index based avalanche susceptibility mapping indicates that the districts in the northwest and southeast areas of the northern zone have the highest avalanche susceptibility. For validation of the final results, Global Hazard Distribution 2.5 minute grid-based developed map of global snow avalanche hazards and landslide was used on spatial based comparison of the resultant cell values, which shows spatial agreement on the distribution of avalanche susceptibility indexes for the assessed susceptible study districts. For better preparedness and planning of avalanche hazard, the present study approach can be applied prospectively by decision-makers on local and regional level.

Keywords: Snow avalanche, Avalanche susceptibility, Northern areas of Pakistan, MCDA, GIS, Topographic factors.

1. Introduction

Snow avalanches (from here-on avalanches) are a critical natural hazard and considered as 'white death' in the snow-covered mountainous terrain, as it pose an abrupt threat to both life and materials. (Singh and Ganju, 2002). Due to the complexity and variations in this physical phenomenon, avalanches are also considered as a major global problem for their occurrence (Burton and Kates, 1963; Tobin, 1997). According to a study data (Prevention web, 2015), in the last three decades, reported major 73 biggest avalanche events have affected approximately 70,000 human lives with addition material cost of 800 million US dollars (USD). To reduce the impacts of such critical disaster the greater understanding about its causation factors, as well as, possible consequences, is a first and major step.

Avalanche is mainly controlled by the variations and interaction of snow and weather conditions with topographic factors. Besides, the external pressure of humans or animals activities and abrupt warming can also add to its abrupt-causation factors (McClung and Schaerar, 2006). The northern areas of Pakistan lie in the Mountainous Range of Karakoram and Hindu Kush-Himalayan range (HKH) which features mostly highly glaciated and avalanche fed terrain (Iliyana et al., 2017). Due to inaccessibility in these areas, field-based monitoring for analyses of topographic parameters on-ground reality basis is mostly lacking to assess the avalanche activity (Greene et al., 2010). However, avalanche release based hotspots are needed to be identified on urgent basis for better mitigation, management, as well as, possible safety of people and property.

The Geographic information system has been applied as a successful approach in determination of natural hazards due to its sophistication in the integration of multi-criteria datasets analysis. Specifically for remote based assessment of the snow avalanche in inaccessible complex terrains, it has been used in many regions globally (Andres and Chueca 2012; Chueca Cía et al., 2014). The GIS-based study approach and related addition of model-based applications comprised the studies focusing different irregular terrain as follows; Avalanche susceptibility mapping of the Nubra valley (Indian Himalaya) region, Nubra-Shyok basin (Indian Himalaya), Czech part of the Krkonoše Mountains (Suk et al., 2011), a simple estimation model for the assessment and zonation of snow avalanche in the Province of Bergamo, Italy (Marana 2017). In addition, developed model-based simulations for avalanche susceptibility includes; vulnerability assessment of mountain environments around the old mining settlement called Magurka, Low Tatras (Slovakia) (Martin et al., 2013), and; snow-avalanche and debris-flow hazard situation, as well as, hazard risk zoning and related approach in the Westfjords (north-western Iceland: Armelle) (Decaulne, 2006). Likewise, based on topographic factors and avalanche simulation model ELBA+, avalanche hazard map large scale was developed covering Asagi Dere catchment in Bayburt city, Turkey (Aydın et al., 2017).

Focusing on the present study region, some study approach has focused on the Himalayan region. These studies include; a generalized linear autoregressive moving average model approach focusing the western Himalayan region, to demonstrate relation between climate warming and increment in the incidence of snow avalanches (Ballesteros-Cánovas, 2018), as well as, assessment of the susceptible zones in limited focused sites with application of RAMMS-avalanche simulation and MTLCIM-XL (Mountain Microclimate-XL) focusing the glaciated terrain of Siachen (Estern Karakoram range of Himalaya, including LOC between Pakistan and India Himalaya (Sardar et al., 2017). While in a recent study it was proposed to develop avalanche information system using terrain parameters from remote sensing data and GIS technology focusing the Indian Karakoram Himalaya (Gusain et al., 2019). However, in the Hindu Kush-Himalayan (HKH) and Karakorum region, including northern areas of Pakistan snow avalanches have left disastrous footprints, as yet; its associated risks and proneness remain poorly determined (McClung, 2016).

The developing trend of MCDA modeling within GIS has been an applicable approach for natural hazard analysis and other geo-environmental studies (Selcuk, 2013) as it provides a multi-approach based techniques based on alternative decisions in solving complex problems with better results (Malczewski, 2006). The MCDA (within GIS environment) based recent study approach on the identification of avalanche hazard while taking into consideration; elevation, slope, aspect, vegetation density, and land use as GIS layers, has been used focusing the area of Bitlis Province, Turkey (Selcuk, 2013).

The scope of the present study was to develop avalanche susceptibility model to produce spatial index based mapping, applying MCDA approach (based on topographic factors as a local function) in GIS. The study area encompasses the selected districts in the northern areas of Pakistan, while field data based topographic factors; elevation, slope, aspect, plan curvature, and profile curvature considered as the critical avalanche causation factors were incorporated as local functions in MCDA model.

2. Study area

The present study area is focused on the Gilgit-Baltistan-districts; Ghizer, Hunza Nagar, Gilgit, Diamir, Astore, Skardu, and Ghanche, as well as, Chitral district of Khyber-Pakhtunkhwa (KP) (Fig.1). Geographically, these districts lie in the northern belt of Pakistan, hence geographically termed as northern areas (Northern zone) of Pakistan. Based on its geological aspect, these areas are located in the Karakorum ranges, which is the part of Himalaya-Karakoram-Hindukush (HKH). The HKH ranges, where the focused districts situate, is the vast mountainous region traversing the borders of Pakistan, India, and China, while towards the northwest spanning the Afghanistan and Tajikistan. In the west of Afghanistan (Wakhan corridor) these ranges cover the majority of –Gilgit-Baltistan (GB-Pakistan). The length of this range is 500 km (approximately), while it is the most heavily glaciated belt of the world, as depicted in Figure 2.

2.1. Data and data-set used: Data Acquisition and Preparation of Causative Factors

In this study, five terrain factors were used as inputs (given in Table 1) which were derived as layers from the elevation (digital elevation model) to generate the landslide susceptibility map. These factors were selected based on their critical role in the triggering of snow to slide downward, thus forming avalanche. The factors were taken and set as follows; Elevation: The critical elevation was taken as; above 4,000 meters (spatial value greater than13123.36 feet). The raster cell values were converted from meters to feet using the Raster Calculator from the Spatial Analyst extension (within Geo-processing/Arc-Toolbox); multiplying the cell-based (spatial) values (from selected raster layer) by 3.2808399. Slope: Values between 30 and 50 i.e. greater than 30 degrees and less than 50 degrees, respectively.

Aspect: The aspect values between 112.5 and 202.5 i.e. greater than 112.5 degrees and less than 202.5 degrees, respectively.

Plan curvature: Values of greater than zero (as a default value for MCDA of the avalanche susceptibility).

Profile curvature: The values of less than zero (as a default value) were considered respectively.

These aforementioned factors were derived as layers in the GIS environment using the algebraic function approach. The data layers were extracted from Digital Elevation Model (DEM) of 30 m resolution acquired from high-resolution Shuttle Radar Topography Mission (SRTM) (Web-Domain: Open Topography, 2018), as the SRTM elevation based raster data (30 m) has relatively greater absolute vertical accuracy than the value of ±16 m (mentioned in the SRTM data specification) (Elkhrachy, 2017).

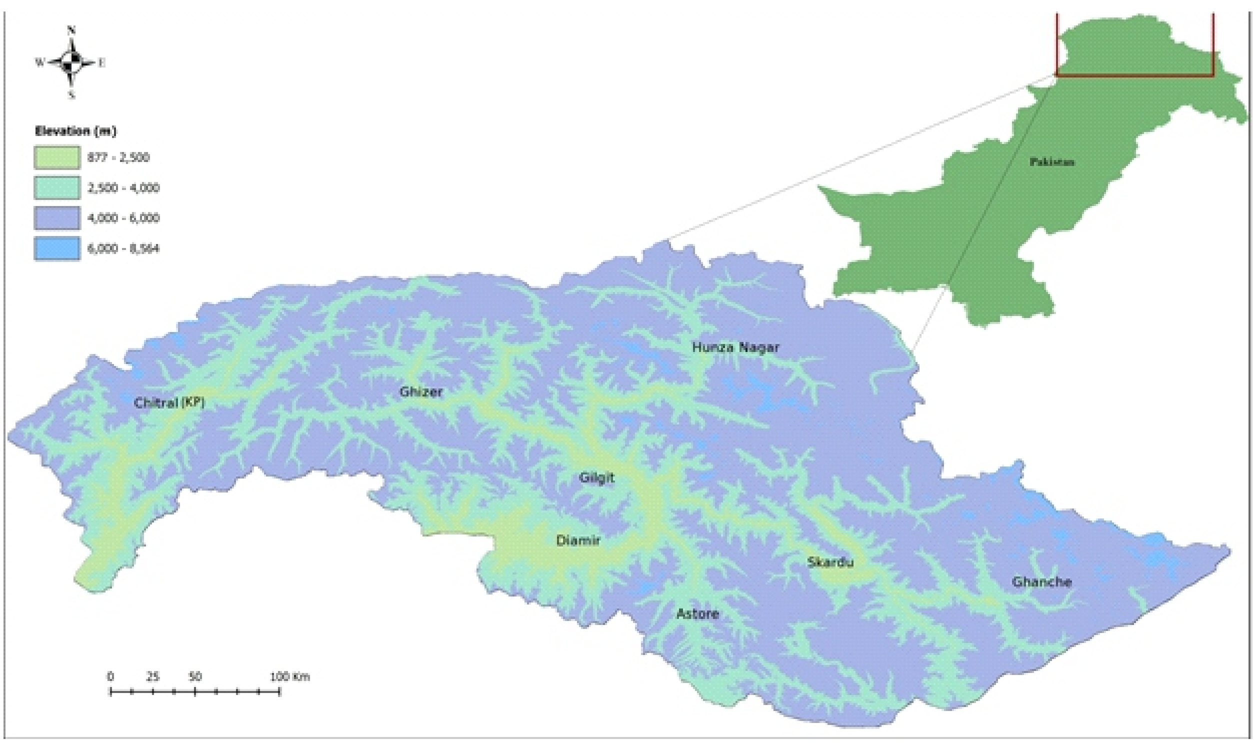

Fig. 1. Elevation based location map of the study area (selected districts) in Pakistan.

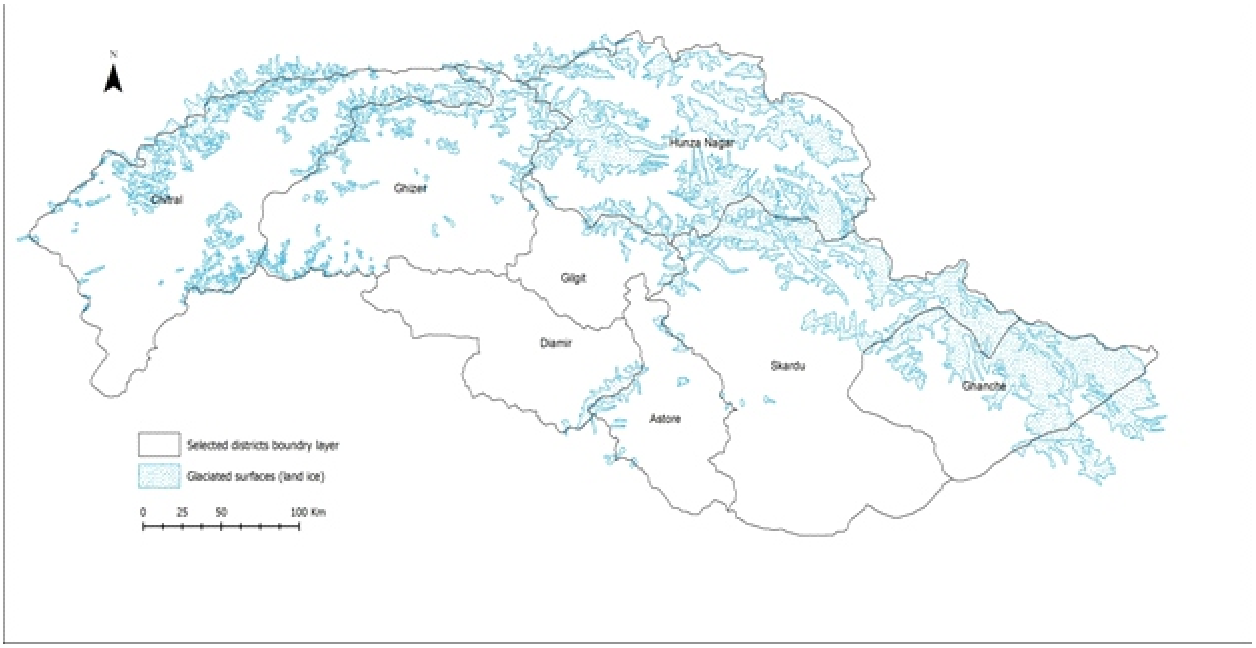

Fig. 2. Glaciated surfaces based map of the study area (selected districts).

Table 1. Major topographic (terrain) factors assigned (considered) as values for criteria (within MCDA based Local function chain)

Sr. No.	Layer (Topographic)	GIS data type	Scale
1	Elevation	Raster (SRTM DEM)	30 m × 30 m
2	Slope	Extracted TIFF (from SRTM raster)	30 m × 30 m
3	Aspect	Extracted TIFF (from SRTM raster)	30 m × 30 m
4	Plan curvature	Extracted TIFF (from SRTM raster)	30 m × 30 m
5	Profile curvature	Extracted TIFF (from SRTM raster)	30 m × 30 m

3. Methodology

The first step of the process was to obtain topographic information of the study area. The main and first-step required inputs for this analysis are a digital elevation model (DEM) of the area, and derived layers from this elevation as multi criteria-based analysis (MCDA). The next step is to calculate the weight values of the GIS layers as input layers. Once all those layers are in place, the avalanche susceptibility index can be calculated as a final spatial (visual) result based on 'Local Function' approach within spatial analyst tools. The 'Local function' analysis tools can be used to perform complex algebra with one or more images (raster layers) to produce a visual result of avalanche susceptibility, by summing up the major critical terrain (topographic) factors as; elevation, slope, aspect, the plan and profile curvature (aforementioned in sections 2).

The determination of avalanche hazard is a relatively difficult task as many factors have role and impact in its triggering. However, the topography based factors, which include; elevation, slope, aspect, and surface features, are considered as constant and critical for avalanche assessment (Selcuk, 2013). The requirements for present study-workflow were three rasters: a DEM with pixel values in feet, a plan curvature calculation (from pixelated values of the DEM) and a profile curvature calculation. Besides, the slope and aspect were extracted from DEM values accordingly. The overall workflow was set and followed in sequential order as;

3.1. Setting up the DEM

Firstly the DEM of the study area was added and set up in Arc GIS (v: 10.3) environment to insert and set up the Local Function. For this purpose, In the Image Analysis window (within Spatial Analysis tools) the DEM was selected and the 'Local Function' was added from 'Raster function Editor-window.

3.2. Setting up a summation of the multi-criterion factors

The next step was to set up the architecture of Multi-criterion topographic factors for the retrieval of spatial results of the susceptibility index. The terrain is a critical factor for the causation of avalanches (McClung & Schaerer, 2006). To set up and perform the algebraic operation within 'Local Function', the DEM with feet values (aforementioned in section 2) was selected to insert Local Function. The operation within Local Function was set to Sum, as to add two DEMs for factors analysis. Similarly, the raster dataset for plan curvature and profile curvature were added (from data disk) respectively. A chain of functions was developed and renamed from Local Function as Sum. Resultantly the five factors-criterions were set up for further analysis on pixel basis (susceptibility index).

3.2.1. To determine spatial values within elevation

On the first branch of the Local Function chain, within the operator 'Greater Than' (scalar) the value from the elevation raster (DEM) was selected as greater than 13123.36 feet (above 4,000 meter) based on cell values. The elevation has no direct effect on the occurrence of snow avalanche occurrence, however; metrological parameters which affects snowpack stability changes with elevation. Hence, the consideration of elevation remains an important terrain factor in the spatial determination of avalanche susceptibility. Besides, the wind speed also increases with an altitudinal variation which increases the wind transported snow. Specifically for the present study area, the critical elevation was taken as greater than 4000 meters. Since the study-area districts lie in the HKH range, It has been observed that in Karakorum Himalaya, more than 80% of the ice cover accumulates above the elevation of 4000 m (between 4000 and 5500 m) (Hewitt, 2011). Additionally; in the central Karakoram and related areas, the maximum ice flux may be observed at 4200–4500 m, as well as, the altitude of about 4000-6000 m is the critical elevations for climatic responses (Hewitt, 2005).

3.2.2. To determine values within slope tolerance

Slope angle is the direct effecting and causation factor for the release of avalanche (McClung and Schaerer, 2006).On the second branch within the Local Function, the Slope Function was added from the second DEM raster. To this Local Function, the pixels based value for critical slope-tolerance was selected with slope range between 30 and 50 i.e. greater than 30 degrees and less than 50 degrees, respectively. We use the values of slope values between 30-50 degrees as both types of surfaces, i.e. dry and wet surfaces, may covered, as well as, according to the related studies the systematic identification of avalanche starting zones ranges between the slope angle of 30 and 50 (occasionally 60) respectively(Schweizer et al., 2003).

3.2.3. To determine values within aspect tolerance

On the third branch, within the Local Function, the Aspect Function (second in the chain/branch) was added (as copied raster) from the first input DEM raster, with selected pixels having an aspect between 112.5 and 202.5 (Aspect: Southeast & South) i.e. greater than 112.5 degrees and less than 202.5 degrees, respectively. The cell-based values which spatially depicts the Southeast-aspect was selected because the solar radiation directly focuses these aspect facets of terrain which leads to ice-melting.

3.2.4. To set the plan curvature and profile curvature tolerance

On the fourth and fifth branches of the Local Function, the plan curvature and profile curvature thresholds were set. Spatial values greater of than zero (as a default value) was set as a threshold value, While for Profile curvature; Pixelated values of less than zero (as a default value) were selected, respectively. The final developed Local Function chain in the GIS environment is given in Figure 3.

The final simulation (iteration) of Local function produced the resultant raster dataset. This spatial result retrieved the resultant pixelated values of susceptibility index with values ranging from zero to five. For the present study approach, we set a values as; zero and one (blue) as no or very low (negligible), while values ranging from one to 2 as low susceptibility for an avalanche, values of two to three and three to four as moderate (yellow) and moderate to high (light orange) susceptibility, while, four to five (red) highly susceptible to avalanche, respectively. In addition, on the basis of raster analysis (raster calculator) the cells with pixelated values greater than 4, i.e. between 4 and 5 was determined and was over-lay on a base-map within GIS environment (in data view) to determine the values of highly susceptible avalanche hotspots as a real spatial basis as a possible approach towards ground-truthing.

4. Results and discussion

A Multi-criteria Decision based Analysis (MCDA) was employed as a new and integrative approach within GIS to produce a snow avalanche susceptibility model. MCDA was set and developed based on topographic factors to produce the avalanche susceptibility of the study area. This approach has become the emerging methods and widely applicable for determination of natural hazards based hotspots, as; it can integrate a large amount of multi-factors data, as well as, reliability in retrieving the weights of enormous numbers of criteria.

The final susceptibility analysis of the study zone was subdivided into the following avalanche susceptibility index: (i) highly susceptible (ii) moderate to high susceptibility (iii) moderate susceptibility (iv) low susceptibility and (v) lowest or no i.e. negligible susceptibility. The boundaries of the categories in the resultant model-analysis were determined by Equal interval-classification (using cell-based values). For avalanche hazards and susceptibility determination, resultant spatial variations based classification method determines the relatively best arrangement of values into comparative classes.

The final snow avalanche susceptibility map (spatial/pixel-based) results indicate that the northwest and southeast areas of the northern region (Northern zone of Pakistan); Ghizer and Skardu districts respectively have the highest avalanche susceptibility. In addition, Chitral and Gilgit districts (northwest) while Ghanche and Astore districts (southeast) respectively have highly susceptible hotspots in discrete places/areas. A relatively low number of highly susceptible avalanche hotspots were determined in the Diamir (Southwest) and Hunza Nagar (northeast) districts, as shown in avalanche based highly susceptible hotspots map (Fig. 5). However, Hunza Nagar, as well as, Ghanche, Skardu, Ghizer districts, and some areas of Chitral district indicate a moderate level of avalanche susceptibility, as shown in spatial results map (Fig. 4).

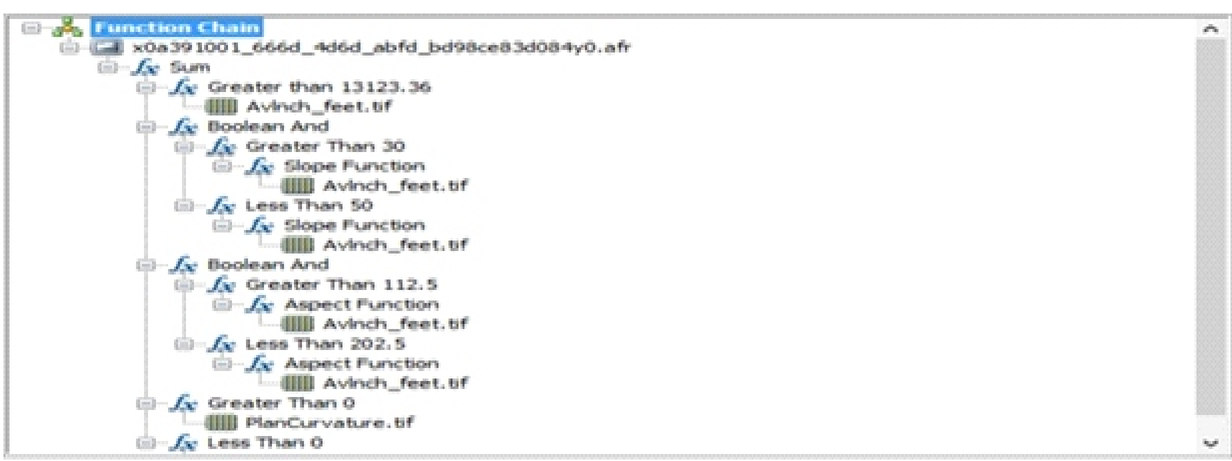

Fig. 3. MCDA Model-based developed Local Function chain

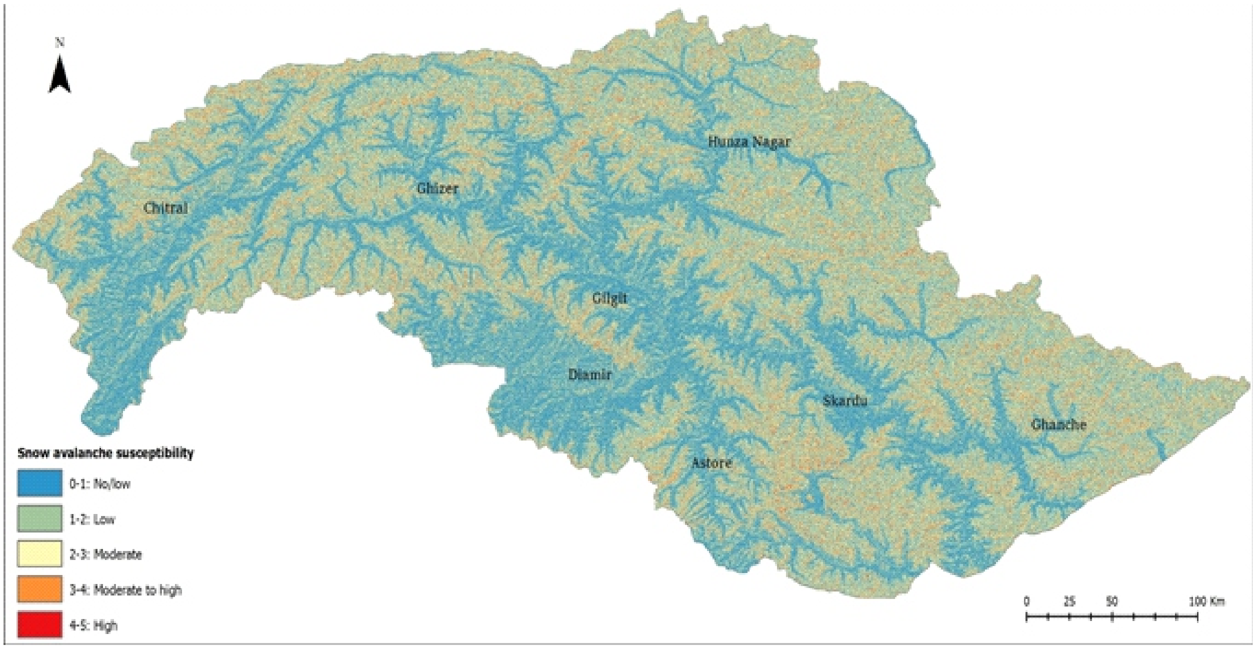

Fig. 4. Snow avalanche susceptibility map (spatial values-based) of study area derived through MCDA approach.

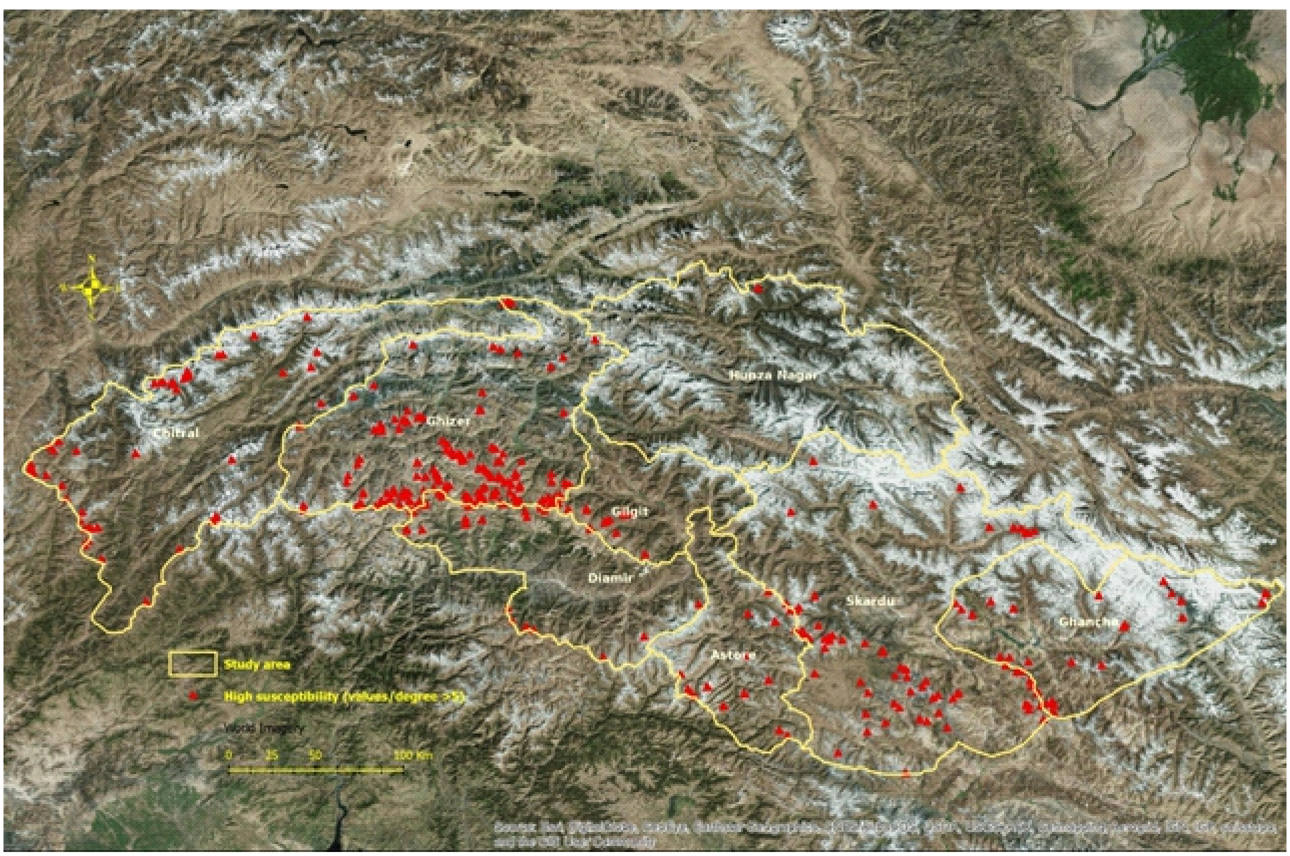

Fig. 5. Avalanche based highly susceptible hotspots within the study area.

4.1. Validation of the avalanche susceptibility model; analysis of the susceptibility maps

The GIS-based MCDA approach has great advantages due to the integration of heterogeneous data and arrangement of spatial data. However, the main challenge of the method is the determination of the multi-criteria based weight values of the GIS layers, as it requires the evaluation on ground truth (filed data) basis. Susceptibility map validation approach follows the comparative analysis of hazards occurrences and its future based probability in the same areas (Kamp et al., 2010). In the present study, we validate the final avalanche susceptibility (resultant mapping) on spatial (pixels) based comparison of the resultant cell-based values. The two separate sets of input data used were: Extracted and developed map, as shown in Figure 6, focusing the study area (within northern zone of Pakistan) obtained from Global Hazard Distribution 2.5 minute grid of global snow avalanche hazards and landslide based upon work of the Norwegian Geotechnical Institute (NGI-CHRR), and; Present study area's resultant map of snow avalanche susceptibility (spatial based: Fig. 4). The comparative analysis indicates that the ratio between the cell-based (spatial) values of avalanche susceptibility (spatial index) over the determined susceptible areas i.e. selected districts and avalanche susceptibility cells based map indicates spatial-agreement on the distribution of avalanche susceptibility classes (indexes). The snow avalanche susceptibility for the Chitral, Ghanche, Skardu, Astore, Gilgit and HunzaNagr districts have similarity in values (spatial index), as shown in maps (Fig. 4, 5 and 6). However the results for some parts of Ghizer and Diamir districts limit the 100 % success and accuracy of validation, but it is due to the differences in aforementioned input data based on incorporated topographic values, as well as, the criteria-based approach.

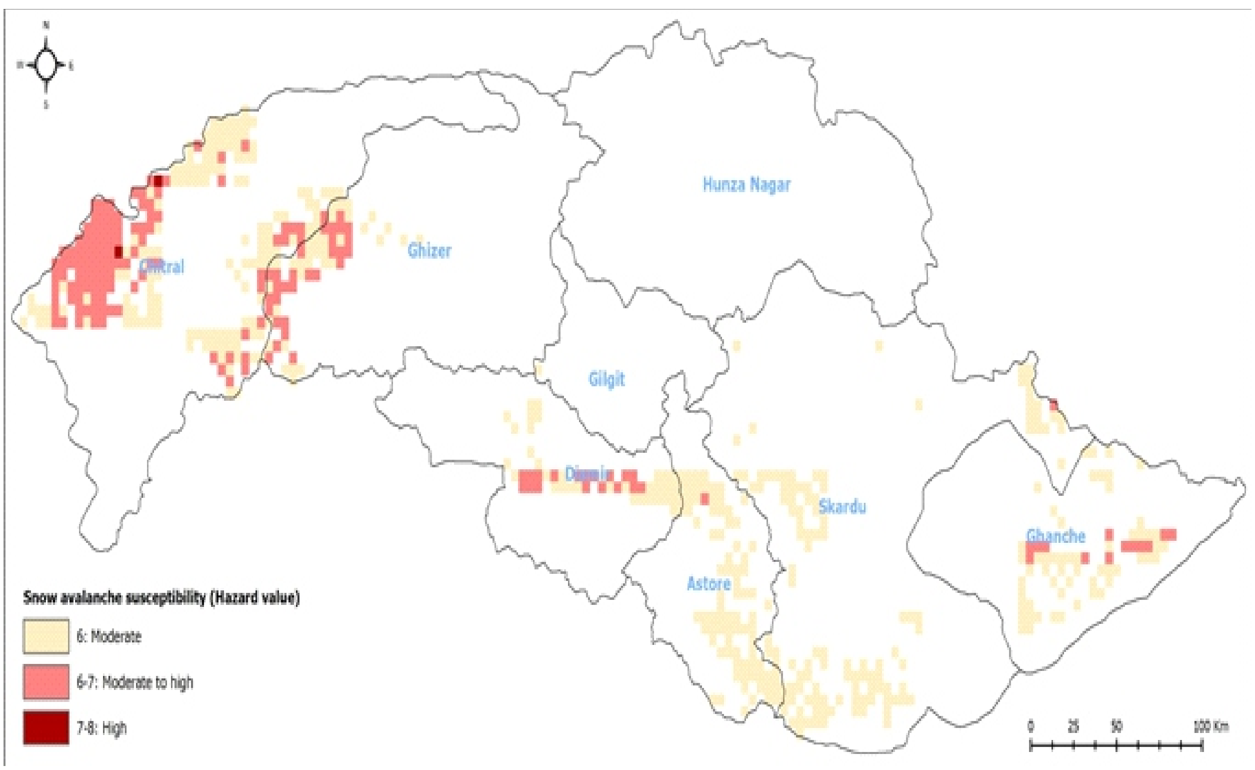

Fig. 6. Observed avalanches in the study area (selected districts); Spatial results based map (Generated and developed from Global Hazard Distribution <2.5-minute grid of global snow avalanche hazards>)

5. Conclusion and recommendations

In the presented study, a Multi-criteria Decision based Analysis (MCDA) was employed, incorporating critical topographic factors as a new and integrative approach within GIS to produce snow avalanche susceptibility model-based spatial results. Based on the achieved results, many areas of the study focused districts in the northern zone of Pakistan are susceptible to moderate and high level of avalanche hazard. For validation, the final avalanche susceptibility (resultant mapping) was compared on a spatial basis with Global Hazard Distribution based grid (2.5 minute) of global snow avalanche hazards map. The comparative analysis indicates agreement on the distribution of avalanche susceptibility based indexes between spatial results basis mapping of MCDA modeled data and global snow avalanche hazard gridded-data. Based on the results it can be stated that; the MCDA with the integration of real-time topographic data within GIS is one of the most reliable approaches to determine and assess the areas susceptible to avalanche-hazard for its better preparedness and management. Besides, for better decision-making, the present approach can be applied by local authorities to determine snow avalanche based proneness on a local and regional basis, in any world-zone. However, it is important to incorporate real-time and field-based data of topographic factors of the focused area. In addition, SRTM DEM data with 30-m spatial resolution have been used in the present study for the extraction of elevation and related critical topographic data, however for more better results; commercial or freely available (if any) High-resolution DEM are recommended.

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Authors' Contribution

Tariq Sardar; proposed the main concept and involved in data collection and processing, major/overall analysis, and write up. Abdur Raziq; assisted in the suggestion of relevant literature and review of the manuscript. Abdur Rashid; assisted in the suggestions regarding review before submission of the manuscript. Ghulam Saddiq; assisted the co-author (Abdur Raziq) in suggestions regarding review before submission of the manuscript.

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