Multi-scale Analysis of the Multi Source DEMs and Derived Topographic Parameters for Suitability of Avalanche Hazard Mapping

Sanjay Kumar Dewali (sk.dewali.dgre@gov.in)  
DRDO Defence Geoinformatics Research Establishment  
https://orcid.org/0000-0003-1122-7537

Kamal Jain  
IIT Roorkee: Indian Institute of Technology Roorkee

Dhiraj Kumar Singh  
DRDO Defence Geoinformatics Research Establishment

Research Article

Keywords: DEM, Topographic parameters, Multi scale analysis, Avalanche mapping

Posted Date: April 28th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1569938/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Multi-scale Analysis of the Multi Source DEMs and Derived Topographic Parameters for Suitability of Avalanche Hazard Mapping

S K Dewali*ª, Kamal Jainª and Dhiraj Kumar Singhª
ªDefence Geoinformatics Research Establishment, Chandigarh, UT, India;
* dewali.sk.dgre@gov.in
ªCivil Engineering Department, Indian Institute of Technology, Roorkee, Uttarakhand, India

Topography is the most essential input in process of avalanche hazard modelling, simulation and mapping. Formation of the avalanches and their movement through mountainous terrain is governed by the topographic parameters and their scales. Digital Elevation Model (DEM) is the only source for deriving various topographic parameters spatially. Spatial resolution and elevation accuracy of the DEMs depend on the DEM sources. In the present work a multi-scale and multi resolution analysis is carried out using six different DEMs (SRTM -90m, ASTER-30m, TOPO-30m, ALOS-12.5m, CartoSat 1-10m, and Airborne Survey DEM -1m) of the Manali-Dhundi area, India. The objective of present work is to understand the variation and sensitivity of various topographic parameters (point and local) at different cell sizes and neighbourhood sizes and also to identify the most suitable scales of different contributing topographic parameters for identification of the avalanche prone areas. High resolution airborne derived DEM elevation is compared with DGPS elevation value and high coefficient of correlation (R2 =0.97), and low RMSE (~0.97 m) and MAE (~0.04 m) has been observed. Further, various topographic variables (i.e. elevation, slope, aspect, curvature, terrain ruggedness) and avalanche simulation parameters (i.e. avalanche release area and debris extents in xyz direction) derived from DEMs were evaluated with the reference DEM at various spatial scales for avalanche sites of study area. Analysis results suggests that, ALOS and ASTER DEM produces fairly matching representation of actual terrain and debris extent with respect to reference DEM. However, TOPO DEM provide good accuracy for calculation of release area as compared to other DEMs. Slope and ruggedness derived from ADS DEM at 5m to 10m resolution provide fairly good representation of avalanche terrain. Extraction of topographic curvature was found most suitable at ≥ 30m resolution for avalanche terrain. Suitable scales for identification of avalanche release area and estimation of avalanche flow extents were found between 5 to 10m. In the present work validation of the estimated release area and flow extent was carried out with the limited point observations from the field. Detailed field investigation using geospatial approach of data collection will be taken in future for detailed and multiple profile-based validation of these results.

Keywords: DEM; Topographic parameters; Multi scale analysis; Avalanche mapping
1. Introduction

Snow avalanche is one of the most common hazards in mountainous regions during winter months. It can significantly affect personnel of these regions, public infrastructure, ecosystems, transport system and residential areas lies in avalanche zones (Arpaci et al., 2014; Blahut et al., 2017; Abdollahi et al., 2019). Avalanche starts from mountain peak with sudden downward motion of a huge snow mass to the valley bottom and it is a common phenomenon in snow-bound mountainous regions. Generally, avalanches flow over an open channel or close gullies in a mountainous terrain and are controlled by its topography. In North West Himalayan regions avalanche occurrences were reported between October and April month due to heavy winter precipitation resulting from western disturbances. In, India during 1970 to 2020 total 2032 peoples died due to the avalanches (SASE Annual Technical Report, 2020). Therefore, mapping of avalanche prone area is essential for the avalanche hazard risk identification, vulnerability assessment, risk reduction and mitigation of avalanche hazards.

Various approaches have been employed for snow avalanche hazard mapping and to generate a susceptibility map using fuzzy-frequency ratio, multi-criteria decision analysis (MCDA) approaches, and analytical hierarchy process (AHP) techniques (Dewali et al., 2009; Buhler et al. 2013, Kumar et al., 2016; Singh et. al., 2019). However, these methods are expert opinion-based, subjective. The accuracy of these approaches depends on accuracy of DEM sources. Few investigators have also used numerical and dynamic simulation approaches to estimate the avalanche hazards (Cama et al., 2017; Casteller et al., 2018), nevertheless a lot of ambiguity is involved in all the modeling input factors when executing to large areas at smaller scales. Veitinger et al. (2016) have developed an algorithm using high resolution DEM for identification of avalanche release area. They have observed
relation between fine-scale DEM-derived parameters such as topography, roughness and snow depth. Maximum correlation was observed between snow surface and terrain roughness. All these models and methods have their own limitations in terms of accuracy and scale of DEM which is basic input parameters because avalanche flow through mountainous terrain is largely governed by the topographic parameters and their scales.

For decades, topographic maps of varying scales have been used for the estimation of topographic attributes for various applications such as hydrology, geomorphology and dynamic modelling (Chapman, 1952; Pike R. J. et al. 1971; Zevenbergen and Thorne, 1987) which is labor-intensive, expensive and time-consuming. Significant improvements in remote sensing technology during last 5 decades have led to higher quality DEMs being generated by different techniques (contour-derived, photogrammetric, LiDAR, and RADAR). Even though DEMs of differing spatial resolutions are freely available (e.g., Advanced Land Observing Satellite Digital Elevation Model (ALOS); Cartosat-1, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER); Shuttle Radar Topography Mapping Mission (SRTM, C and X-band)), choosing an appropriate type and scale of DEM for specific purposes still remains a question in avalanche hazard mapping applications.

A number of literatures have been published across the globe during last few decades to evaluate the association between the resolution of DEM, accuracy, data quality, sensitivity, and modeling ambiguity for different landscape applications. Florinsky and Kuryakova (2000) has reported statistical method to estimate acceptable DEM scale resolution range for landscape modelling in Eastern European Plain at a micro-scale for soil moisture. In this study, at varying scale resolutions between 1 m to 7 m different terrain features have been generated from DEMs, and targeted biophysical property and a correlation coefficient has been estimated. Analysis demonstrates 2.25 m-3.25 m optimal scale DEM resolution for biophysical property modelling. Miliaresis and Paraschou (2005) has estimated various
terrain features using SRTM level 1 DEM and evaluated with 1:250,000 topographic maps for Crete Island lies in Southern Greece. Authors observed 25 m as overall accuracy and high mean error in NW, W and SW aspect as compared to other terrain features. Aguilar et al. (2005) recommended that terrain morphology as the most significant aspect to estimate the DEM accuracy as compared to sampling density and interpolation techniques. They observed mountainous topography have larger DEM errors as compared to flatter terrains due of dense-vegetation-canopy, snow cover area and rugged terrain complexity, (Nelson et al., 2009). Zielinski and Chmiel (2007) estimated terrain features for forests, agriculture and mountainous regions using SRTM C-band DEM and observed that SRTM version-II has higher accuracy as compared to standard SRTM DEM, therefore it can be used in various applications. Vaze et al. (2010) reported that DEM-derived hydrological indexes are sensitive towards source, resolution and accuracy of DEM and good quality of DEM can be used for many applications and models (Renschler and Harbor, 2002; Merritt et al., 2003). Earlier, studies were published for DEMs accuracy assessment in terms of RMSE at specific locations, however, limited studies were reported across the globe, evaluating the errors in image collection techniques, source of data, sampling technique, spatial resolution of DEM, DEM generation methods and effect of topographic for various land cover features (Florinsky, 1998; Thompson et al., 2001; Chaplot et al., 2006). Bühler et al. (2012) compared DSMs generated using optical ADS80 and LiDAR system at 25 cm Ground Sampling Distance (GSD) over Dorfbach, Switzerland and observed RMSE less than 1 m and upto 2 m for slope < 50° and > 50°, respectively. Rawashdeh (2012) evaluated the Digital Terrain Model (DTM) at scale of 1:25,000 topographical maps for hydrographical and drainage network and observed that DTM-derived drainage network pattern using photogrammetric process revealed good correlation with the actual. Various researchers (e.g. Kale and Shejwalkar, 2007; 2008; Magesh et al., 2011; 2013; Prasannakumar et al., 2011; Jayappa et
al., 2012; Shinde et al., 2013) have used DEMs-derived parameters for geomorphometric applications in Western Ghats river basins. Thomas et al. (2014) have reported the sensitivity of various spaceborne DEMs over Indian mountainous regions of Western Ghats river basins. Authors observed that SRTM has high vertical accuracy with respect to ASTER and GMTED in spite of coarser resolution and accuracy of DEMs were influenced by vegetation types. Gupta et al. (2014) compared SRTM-X band generated DEM with ADS80 photogrammetric for mountainous region of Himachal Pradesh, India and observed the accuracy of ~75.20 m. Deo et al. (2016) compared the high-resolution DEM generated using TanDEM-X images with Cartosat-1 DEM and observed that high resolution TanDEM-X DEM has higher RMSE due to shadow and layover effects as compared to Cartosat-1 DEM. However, during last few decade hardly any efforts have been made by the researchers to measure the sensitivity, accuracy, and applicability of various DEMs for snow avalanche hazard mapping in the Western Himalayan regions, India.

In current study, an effort has been made to identify most suitable data source, scale and resolution for avalanche hazard mapping using different DEMs (i.e., SRTM-90m, ASTER-30m, TOPO-30m, ALOS-12.5m, CartoSat-10m and Airborne Survey DEM-1m) of the Manali Dhundi area, India. First, the reference DEM (Airborne Survey DEM) has been compared with ground collected elevation values acquired through Differential Global Positioning System (DGPS) and analysed. Further, all the DEMs have been analysed at their original cell sizes and also at the resampled dell sizes (1m, 10m, 30m and 90m). Various terrain parameters (i.e., elevation, slope, aspect, curvature and terrain ruggedness) and avalanche simulation parameters (i.e., release area and debris extents) were also derived for all DEMs and compared with reference DEM to estimate suitable scale and source. The validation of the DEM derived avalanche parameters was carried out using field data.
2. Study Area

Study area of current analysis is Manali-Dhundi region, Himachal Pradesh (HP), lies in lower range of Indian Western Himalaya, and presented in figure 1(a-b). Manali-Dhundi region is part of Beas River basin and originates from eastern side slopes of Rohtang Pass, Beas Kund glacier at an elevation of 3900 m m.s.l. Region receives maximum ~50% of snow cover area (SCA) during peak winter period and 32 days per 500 m snow cover days (SCD) with rising elevation (Sharma et al., 2014). It comprises of high mountainous regions of Kullu, Lahaul & Spiti district of HP and Palchan, Solang, Dhundi and Teling of Manali area. The region is well-known for ski slopes, natural beauty, mountaineering, tracking and recreational activities across the globe, and millions of tourists visit every year. It contributes significantly in the state budget. The altitude of the area varies from 2138 m to 6171 m m.s.l with means ~3953 m m.s.l. Study area has complex topography, narrow valleys, steep slope, high slope gradient.

Snow and meteorological observation station of Defence Geoinformatics Research Establishment (DGRE), Chandigarh (formally known as Snow and Avalanche Study Establishment (SASE)) lies at 3050 m m.s.l altitude at geographical position of 77° 06′ longitude, 32° 21′ latitude so-called “Dhundi”. Singh et al. (2018a, 2021) has reported mean snowfall of ~11.5 m and mean temperature of ~1.6, -1.2, -0.4, and 3.1°C for December, January, February, and March respectively during winter seasons (1989-2012). Through Manali-Leh highway study area joins the HP state with union territories Ladakh and during winter period a number of avalanche activities were reported along this high way. On an Average 14 avalanche occurrences have been observed per year during the study period and shown in Figure 1c. In 2004-2005 maximum ~63 avalanches have been observed, this may be due of western disturbances cause heavy snow fall in the study area (Sharma et al. 2014; Singh et al. 2018a, b; Singh et al., 2019). Some of these occurrences also caused avalanche...
accident leading to fatality and infrastructure damages. The data revealed that accurate
efficient avalanche hazard assessment and management in this region is essentially required
to minimise the losses due to these events. DGRE has marked the prominent avalanche sites
in this area, it starts from Manali South Portal-1 (MSP1) close to Manali and continue up to
MSP13, right at the entrance of the Atal tunnel (21 km stretch).

Present study and analysis is focused on Beas Basin having area 1063 km². In the
present work, an avalanche prone region of the study area is taken for the detailed
investigation in order to understand the effect of multi-source DEMs and its parameters on
avalanche hazard analysis variability at avalanche site scale (local scale). Figure 1d shows the
enlarged view of one of avalanche site (MSP-10) of study area and has the runout zone in
valley bottom (2787 m m.s.l.) and formation zone at an elevation greater than 3732 m m.s.l.
This area has been chosen as because of the avalanches in this region affects the life line link
of this area (Manali-Leh national highway) near the Atal tunnel and availability of the high-
resolution aerial photogrammetric DEM of this area as a reference data.

3. Data Used and Source

In present study, six multi-resolution and multi-source DEMs (Airborne Survey DEM
(generated from digital aerial photogrammetric data), Cartosat-1 (Carto, generated from
Cartosat-1 images); Advanced Land Observing Satellite (ALOS,
[https://search.asf.alaska.edu/](https://search.asf.alaska.edu/)); TOPO (derived from SoI toposheets), Advanced Spaceborne
Shuttle Radar Topography Mission (SRTM, [http://glcf.umiacs.umd.edu](http://glcf.umiacs.umd.edu)) to derive various
topographic variables (i.e. elevation, slope, aspect, curvature, terrain ruggedness) and
avalanche simulation parameters (i.e. release area and debris extents) at various spatial scales
for MSP-10 avalanche site. Sensitivity of various topographic parameters (point and local)
are examined at different cell sizes and neighbourhood sizes. Remote sensing-based DEMs, source, resolution and generation type used in this study is given in Table 1.

### 3.1. Airborne Survey DEM

The high-resolution DEM (generated from ADS80 images) over Manali-Dhundi and neighbouring regions at 1-m spatial resolution was acquired from the DGRE, Chandigarh. ADS80 DEM was generated using stereo pair photogrammetric survey images at 40 cm GSD and used as reference elevation source for comparison of other DEMs.

### 3.2. Cartosat-1 DEM

To provide accurate and reliable elevation of terrain over the Indian regions Cartosat-1 mission was launched in 5 May 2005 by using the stereo dataset and this project was started by Indian Space Research Organization (ISRO). CartoDEM is created by processing stereo-pair Cartosat-1 images using limited ground points. The database was structured as a directory of DEM and orthoimage for the entire Indian regions frame with DEM posting of 1/3rd arc second (about 10 m at the equator). Agarwal et al. (2019) has reported ~8 m and 15 m accuracy of elevation and planimetric, respectively. The DEM at 30m spatial resolution is freely available and can be download from https://bhuvan.nrsc.gov.in/ website in Geo-Tiff format. In this work, the Cartosat DEM was generated at 10 m spatial resolution by processing the Cartosat (A and F) stereo pair images of 2.5 Ground Sampling Distance (GSD).

### 3.3. Advanced Land Observing Satellite (ALOS) DEM

ALOS is freely available DEM at the spatial resolution 12.5 m and can be download from https://search.asf.alaska.edu/. The DEM is available as two product levels: high-resolution and low-resolution. Both high-and-low resolutions have provided DEM at 12.5 m and
provided by Japan Aerospace Exploration Agency (JAXA) in Geo-Tiff format (Hu et al. 2017). The ALOS DEM is considered one of the most accurate global elevation dataset (JAXA 2015). Most of the available DEMs are geoid-based and require a correction before they can be used for terrain correction. The ALOS DEM available at Alaska Satellite Facility, a radiometrically terrain corrected (ASF RTC) product that is converted from the orthometric height of the source DEM to ellipsoid height using the ASF MapReady geoid_adjust tool. This tool applies a geoid correction so that the resulting DEM relates to the ellipsoid.

3.4. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM

The ASTER images are available at variable spatial resolution between 15 m to 90 m. It comprises of three sensors: the visible and near infrared (VNIR), the shortwave infrared (SWIR) and the thermal infrared (TIR), where VNIR is the only one that provides stereo images. It is a joint mission between NASA and the Japanese Ministry of Economy, Trade and Industry (JMETI) and this data is available on earthexplorer.usgs.gov website. The ASTER DEM was created through image matching method and available for ~99% of the global land (Hu et al. 2017). ASTER DEM has ~15 m horizontal accuracy and ~15-25 m vertical accuracy based upon environmental condition of the area. Toutin (2008) has addressed in-depth review the approaches, algorithms and software used for ASTER DEM generation and deliberated the use of ASTER DEMs for different geoscientific and geomatic applications.

3.5. TOPO DEM

The TOPO DEM at 30m spatial resolution generated by DGRE using SoI (Survey of India) toposheets. Toposheets at 1: 50,000 scale have been scanned and georeferenced to actual coordinate system of study area. Further, contours at 30 m intervals and spot heights have
been digitized in ArcGIS using topographic maps. To certify quality of contour data, topology is produced and errors are estimated and corrected. The digitally retrieved contour elevation data from toposheets is then converted to raster TOPO image at 30 m resolution in ArcGIS spatial analyst tool (Reuter and Nelson, 2009).

3.6. Shuttle Radar Topography Mission (SRTM) DEM

The SRTM DEMs are the combined effort of National Geospatial-Intelligence Agency (NGA), National Aeronautics and Space Administration (NASA), Italian Space Agency (ASI) and German Aerospace Centre (DLR (Rexer and Hirt, 2014). SRTM DEM is freely available and can be downloaded from [http://glcf.umiacs.umd.edu](http://glcf.umiacs.umd.edu) website. SRTM DEMs for entire earth generated using interferometric synthetic aperture radar method (InSAR; Zebker and Goldstein, 1986). with C-band of wavelength ~5.6 cm and X-band of wavelength 3.1 cm Rabus et al. (2003). SRTM DEM elevation information is available at ~90 m and ~1 km spatial resolutions world, except for UA (~30 m). In SRTM DEM relative vertical (linear) error is 10 m and geolocation (circular) error is 15 m in 90% of data. More detailed and critical reviews of SRTM DEM datasets accuracy, errors, applications etc. are published by Rodriguez et al. (2006), Farr et al. (2007) and Jarvis et al. (2008). In the present study we have used the SRTM DEM of 90m spatial resolution.

4. Methodology

In the present paper, adopted methodology is given in Figure 3. Remote sensing data’s have been processed using ArcGIS 10.8 software. Different sources and spatial resolutions of DEMs (i.e., SRTM-90m, ASTER-30m, TOPO-30m, ALOS-12.5m, CartoSat 1-10m and Airborne Survey DEM -1m) have been used in this analysis. The processing workflow adopted for this study is broadly divided in following four parts.
4.1 Accuracy parameters for DEM Analysis:

According to American Society for Photogrammetry and Remote Sensing (ASPRS) report 2014, vertical accuracy is most significant parameter of the quality of DEM. However, horizontal accuracy of a DEM is also importance because it has a huge influence on the vertical accuracy (Seferick et al. 2013). A comprehensive review of methods and practices for the accuracy assessment of DEM is summarised by José L et al. (2020). DEM accuracy is primarily categorised in to two classes (1) absolute vertical accuracy, and (2) relative vertical accuracy. The absolute and relative vertical accuracy refers to the accuracy pertaining to Geodetic-Cartographic Reference System and local reference system respectively. Relative accuracy is more appropriate for local investigation and associated to the parameters (slope and aspect, ruggedness etc.) estimated from the neighbourhood. Florinsky et al. (1998), suggested not to use the term error in the accuracy estimation of a DEM, since this term is inadequate, because reference DEM values have its own uncertainties.

Authors have recommended the term elevation discrepancies between different DEMs elevation. The DEM vertical accuracy represents the accuracy of elevation at any location and related to the discrepancies $d$ estimated by comparing DEM product elevation ($h_{DEM}$) and reference DEM elevation ($h_{REF}$) at a specific location $i$. Accuracy assessment measures the trueness (absence of bias) and precision (measure of dispersion) in DEMs, and can be estimated from equation given bellow,

$$d_i = h_{DEM_i} - h_{REF_i}$$ (1)

$$\mu_d = \frac{1}{n} \sum_{i=1}^{n} d_i$$ (2)

$$\sigma_d = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (d_i - \mu)^2}$$ (3)
\[ MAE = \frac{1}{n} \sum_{i=1}^{n} |d_i| \]

\[ RMSE_d = \sqrt{\frac{1}{n} \sum_{i=0}^{n} (d_i)^2} \]

where, \( h_\text{DEMi} \), \( h_\text{REFi} \) and \( d_i \) is elevation of DEM products, reference DEM elevation and discrepancy in position \( i \). Mean, standard deviation, mean-absolute-error and root-mean squared-error of discrepancies is represented by \( \mu_d \), \( \sigma_d \), \( MAE \) and \( RMSE_d \), respectively.

However, \( n \) denotes number of samples.

Since RMSE is closely associated with DEM data generation techniques and accounts for both random and systematic errors introduced during the data generation process, it is widely used as an overall indicator for accuracy assessment of DEMs (Nikolakopoulos et al., 2006; Reuter et al., 2009; Mouratidis et al., 2010). Statistical measures given in the equations (1) to (5) are used for accuracy analysis of different data sources with respect to ground observations and ADS80 DEM.

### 4.2 Accuracy assessment of Reference DEM:

Initially, high resolution airborne ADS80 DEM were compared and evaluated with the ground survey DGPS collated elevation value. The DGPS collected values at 20 locations have been used in this study for the evaluation and to get millimetre positions have been estimated using dual frequency DGPS with Trimble R7. Figure 4, shows the comparison between ADS80 DEM extracted elevations and DGPS elevations values and associated elevation error. The coefficient of correlation (R2), RMSE and MAE was observed 0.99, 0.97 m and 0.04 m between ADS DEM and DGPS elevation values. The minimum and maximum error was observed -1.42 m and 1.36 m. Therefore, high resolution airborne ADS80 DEM has been used to evaluate the other DEMs.
4.3 Comparative Analysis of Multisource DEMs with Reference DEM:

All the five different DEMs considered for the present study were compared with reference ADS80 DEM. All the analysis of the different DEMs has been carried out at their original cell sizes and at rescaled respective DEM cell size. All the DEMs have been rescaled to common spatial scale resolution (Nikolakopoulos et al., 2006; Prasannakumar et al., 2011). Therefore, a pixel spatial resolution of 1m, 10m, 12.5m, 30m, 90m is set as the spatial scale for investigation and all the DEMs have been resampled to 1m, 5m, 10m, 20m, 30m and 90m using bilinear interpolation technique. Further, to eliminate the false outlier’s 3 x 3 kernel neighborhood low-pass filter has been applied to resample DEMs, and horizontal and vertical shifts in DEMs were corrected using Co-registration with ground control points (GCPs) collected from the DEM. For the evaluation of various DEMs following three types of data selection methods were used, (a) Elevation along a line profile in avalanche flow path, (b) Elevation values at the regular grid points with 5m spacing in avalanche prone area and (c) Elevation and derived topographic parameters of the different DEM raster at original and different resampled cell sizes of the study area.

4.4 Multisource DEMs Analysis for Avalanche Simulation Parameters:

The snow avalanche release areas information is essentially required for numerical simulation of avalanche events for planning mitigation measures, for hazard mapping and to secure important roads. The release mechanism and flow of snow avalanches depends on many different terrain, meteorological, snowpack and triggering parameters and their interactions, which are very difficult to assess. In many alpine regions such as the Indian Himalaya, nearly no information on avalanche release areas exists mainly due to the very rough and poorly accessible terrain of large snowbound regions and the lack of avalanche records. This highlights the dependency of retrieval of avalanche release information on DEM based
To evaluate the effect of DEM sources and scale (cell sizes) in avalanche area identification and mapping, two avalanche parameters namely avalanche release area and avalanche debris extent were considered in this study. The avalanche release area was estimated using methodology given by Buhler et al. (2013) and to estimate flow extents of avalanche debris, the avalanche numerical flow simulation model developed by Christen et al. (2011) was used. Both the models require DEM as one of the input parameters. In order to understand the effect of DEM cell size and source on release area and debris extent, the above models were executed for each DEM source and cell size by keeping other parameters fixed. Table 2 provides the values of required input parameters used for these models in present study.

5 Results and Discussion

The precise information of avalanche hazard zones, release area and its debris extents are essential for mapping, monitoring and forecasting of avalanche hazards and also for the avalanche safety assessments of the infrastructure installed in the mountainous regions. These parameters are extracted using DEM and their accuracy depends on the source DEM. In present study, multi-source and multi-resolution DEMs were examined with respect to reference DEM at different scales to estimate optimum scale and source for avalanche hazard mapping.

5.1 Comparative Analysis of Elevation of Multisource DEMs

Elevation is an essential parameter that affects the snow avalanche events in snow covered-regions, due to variability in snow–meteorological parameters (e.g., snow depth, rainfall, speed of wind, snow surface temperature and snowfall) with varying elevations (McClung and Schaeerer 2006) and widely used in avalanche hazard mapping and modelling. Lower
elevation regions receives less snowfall and having dense forest, therefore less avalanche susceptible, compared to high elevation. The distribution of elevation values at any point and around its neighbourhood area decides all the topographic parameters in that area. So, the accuracy of the elevation values of data source greatly affects the accuracy of derived topographic parameters. The 3D hillshade maps of MSP-10 avalanche site for ADS, Carto, ALOS, TOPO, ASTER and SRTM are given in figure 2. Overall elevation statistics of these data sources for this region is given figure 5. The mean and minimum elevation values of the all datasets seem to close to one another, whereas the maximum elevation values show the large variability.

The lowest elevation of MSP-10 retrieved from ADS is 2783 m above m.s.l., whereas that of Carto, ALOS, TOPO, ASTER and SRTM is 2783 m, 2793 m, 2792 m, 2815 m and 2792 m above m.s.l., respectively. In MSP-10, SRTM has the highest elevation value 3803 m above m.s.l., whereas other DEMs have values in the range of 3514 m (Carto) to 3803 m above m.s.l. (SRTM).

5.1.1 Elevation variability along the avalanche flow path profile:

To understand the variability in elevation values of different data sources in the direction of avalanche flow path, a linear profile of each data source was drawn. Figure 6 show the variability of elevation values of these profiles. The elevation values at all the points of line profile for reference DEM were found lowest. The maximum variations and highest elevation values were observed for TOPO DEM. The saw tooth pattern was observed in the elevation values all data sources, other than ADS DEM and the size of sawtooth was found increasing with increasing cell size. This sawtooth pattern is attributed to the cell size of the data and interpolation technique used in data preparation.
5.1.2 Elevation Variability Analysis using Regular Grid Centre Points:

Statistical parameters for the elevation distributions of different elevation DEMs (at original resolution) were derived from the regular grided data sampled at 5m spacing. For this the centre points of square grid of cell size 5m were considered (figure 7a). The elevation values at these grid centre points of each DEM source were extracted and the histogram for each dataset was prepared (figure 7b). The histograms show that the datasets follow normal distribution with variability in $\mu \pm \sigma$ (varying from 3102m $\pm$ 208m for ADS DEM to 3208m $\pm$239m for TOPO DEM) and elevation maxima (varying from 2925m for ADS DEM to 3225m for TOPO DEM). As shape of histogram is largely governed by the binning interval of data. In order to ascertain that, the elevation values of different data sources in our study area follows the normal distribution, the probability plot (Q-Q plot) for each dataset was generated (Figure 7c). Q-Q Plot shows a graph with an observed cumulative probability in percentage on the X axis, an expected cumulative probability in percentage on the Y axis and reference line as ideal normal distribution. Figure 7c illustrates that all datasets follow the normal distribution with $\mu$ (varying from 54.10 for carto DEM to 63.33 for SRTM DEM) and $\sigma$ (varying from 33.11 for SRTM DEM to 36.55 for ASTER DEM). The scatter plots of the elevation values of different elevation sources with respect to reference ADS DEM is presented in figure 7d, all scatter plot shows the over estimation of the elevation values by all data sources in comparison to ADS DEM. Bias and Mean Absolute Percentage Errors (MAPE) were calculated for each dataset and maximum bias (-107 m) and MAPE (79%) was found for TOPO DEM data and minimum bias (-7 m) and MAPE (15%) was found for ALOS DEM.

5.1.3 Spatial Distribution of Elevation Values over Avalanche Area:

To evaluate the elevation distribution of different DEMs over an avalanche prone region, the
binning of the elevation values is done in different ranges. Analysis of the binned elevation images of different DEMs (Figure 8) illustrates that the elevation distribution patterns vary different data sources. The TOPO and SRTM DEMs are showing the largest and smallest range of elevation variations respectively.

5.2 Comparative analysis of Multi-source DEMs at multi resolution

The effect of resampling of the multi-source elevation data at four different cell sizes is analysed in this section. To achieve this the four resampling cell sizes 1m, 10m 30m and 90m were considered corresponding to original spatial resolution of ADS, Carto, TOPO and SRTM DEM. After resampling the data using bilinear interpolation method, all data sources at same resolution (i.e., 10m) were compared with the data source (i.e., Carto DEM original resolution 10m) having the original cell size at that resolution. In this analysis terrain elevation, slope, ruggedness and curvature were considered.

5.2.1 Elevation:

Comparison of elevation values of resampled DEMs at different spatial scale with respect to DEMs having original cell size at that resolution is shown in figure 9. The high value of R2 and minimum MAE was observed in ALOS and ASTER DEM at all resolution. At the 90 m resolution all DEMs have approximately equal MAE. The MAE in ALOS and ASTER was observed 11.5 m and 31.4 m at 1 m spatial scale, whereas 29.3 m and 30.5 m at 10 m scale, 17.4 m at 30 m scale. However, TOPO DEM has large MAE at all the different scales.

Figure 10 shows spatial and frequency distributions of elevation differences between multi-source DEMs at their original spatial resolutions and reference DEM resampled at these resolutions. The maximum elevation differences have been observed in the forested and shadow regions of the study area. For most of the regions of study area, the multisource DEMs are overestimating the elevation values as compared to reference DEM at these
resolutions (Figure 10(a) to 10(e)). The minimum mean elevation difference is observed in ALOS DEM (~6 m) and maximum in TOPO DEM (~62 m).

An avalanche moves down a slope it follows a flow path, that primarily dependent on the slope's degree of steepness and the volume of snow/ice involved in the mass movement. Figure 11 shows the elevation error along the avalanche flow path. Elevation along avalanche flow paths have been extracted from different DEMs and compared with reference DEM at different resolutions. It is observed (figure 11) that ALOS DEM provide low RMSE (~35 m) and Mean Error (ME) (~32 m) as compared as compared to other DEMs. The high value of RMSE and ME is observed for TOPO DEM as ~149 m and ~134 m, respectively. All the DEMs elevation overestimate as compared to reference DEM at different resolution. Avalanche flow path extracted at same scale (~30 m) using different DEM sources (TOPO and Aster) have different elevation profiles and error values this may be due to different DEM generation techniques of these datasets. RMSE and MAE in ASTER, Carto and SRTM DEM was observed as 37.3 m and 34 m, 45 m and 41 m and 85 m and 83 m respectively.

5.2.2 Slope: Slope is defined as the rate of change in elevation in the path of vertical descent and has major influence on avalanche hazard mapping and avalanche simulation models. It is a vital parameter for hazard assessment, as it affects the snow mass flow due to gravity. Hence, the maximum priority and weightage were assigned to this terrain parameter in the process of avalanche mapping. Comparison of slope angle values of resampled DEMs at different spatial scale with respect to DEMs having original cell size at that resolution is shown in figure 12a & b. Slope maps were generated for all the resampled DEMs at 1m, 10m, 30m and 90m spatial scale. In an avalanche site (MSP-10), the range of slope angle values derived different DEM sources (Carto (3° to 67°), ALOS (1° to 68°), TOPO (4° to 62°) and ASTER
(2° to 63°) shows better similarity with that of reference ADS DEM (0.2° to 72°), while the slope of SRTM shows a relatively narrow range (i.e., 9° to 55°). The mean slope of ADS, ALOS, Carto, TOPO, ASTER and SRTM DEM was observed as ~38.6°, ~33.8°, ~35.3°, ~38.6°, ~34°, and ~33.7° respectively. ADS and TOPO DEM has equal means slope, whereas SRTM DEM has lower value of mean slope. The minimum and maximum MAE was observed in ASTER (6.6° to 10.32°) and TOPO DEM (9.77° to 24.28°) as compared to other DEMs. ASTER and TOPO DEM has 9.88° and 24.28° MAE at 1 m spatial scale, whereas 10.32° and 12.09° at 10 m scale, 6.6° and 9.77° at 30 m scale. The boxplots given in figure 12b show the overall slope statistics of multi-source DEM at different scales. At higher spatial resolution (1m) more slope variability has been observed. Whereas, at the moderate to low resolutions (10m, 30m and 90m) all the DEMs represents approximately similar slope distributions.

Figure 13 shows spatial and frequency distributions of slope differences between multi-source DEMs at their original spatial resolutions and reference DEM resampled at these resolutions. For most of the regions in study area slopes values are overestimated as compared to reference DEM at different DEMs resolution. The minimum mean slope difference is observed in TOPO DEM (-0.08°) and maximum in ASTER DEM (-4.7°), whereas Carto, ALOS and SRTM have -4.6°, -3.3° and -2.9° respectively.

The formation zones of the avalanches generally have the slopes values 250–450, the track zones of the avalanche usually occur on a 250–300 slope and the runout zone where avalanche retards and stops. This usually occurs when the slope has reached a steepness that is less than 120. Slopes of the MSP-10 avalanche site has been classified into four classes (i.e., < 12°, 12°–25°, 25°–45° and >45°) (Maestro et al. 2003). Figure 14 shows the error in slope values along the avalanche flow path. It is observed from figure that ASTER DEM has low RMSE (10.1°) and ME (-2.8°) as compared to other DEMs. Difference in slope values is
observed positive for smaller slope angles (<120) and negative as slope angles are increasing along the avalanche flow path. Carto, ALOS, TOPO and SRTM DEM has RMSE and MAE as 15.89° and -8.7°, 15.36° and -7.1°, 14.86° and -9.2°, 12.32° and -4.1°, respectively.

5.2.3 Terrain Ruggedness:

Topographic roughness another important parameter to have a significant influence on avalanche release and avalanche flow. It has been reported that a very rough and irregular surface (rocky outcrops, logs, etc.) hinders the snowpack in the downward motion (McClung, 2001). Further, rough terrain features can prevent the formation of continuous weak layers, necessary for the occurrence of large fractures in the snowpack (Schweizer et al., 2003). However, all above mentioned stabilizing effects disappear if the snowpack is deep enough to form a relatively smooth surface. Terrain roughness may then even have a destabilizing effect by adding additional stress to the snowpack and favoring snow metamorphism processes near rocks (McClung and Schaerer, 2006). Topographic roughness is very less explored in DEM accuracy assessment for avalanche mapping and modelling point of view (Maggioni and Gruber, 2003). The mean roughness of MSP-10 avalanche site extracted from ADS is 2.3, whereas that of Carto, ALOS, ASTER, TOPO and SRTM is 24.5, 30, 57.9, 64 and 165, respectively. In MSP-10, SRTM registers a maximum roughness of 311. Comparison of topographic roughness values of resampled DEMs at different spatial scale with respect to DEMs having original cell size at that resolution is shown in figure 15a & b. The minimum MAE (16 to 34) was observed in ALOS data for all spatial scale up to 30m. In case of 90 m resolution all DEMs have large value of MAE as compared to other small scale DEMs. The MAE in ADS, ASTER, TOPO and SRTM was observed between 28 to 172, 28 to 155, 24 to 109 and 112 to 121 respectively at different DEMs resolutions. However, SRTM DEM has large MAE at all the scales as compared to other DEMs at similar scales of other DEMs. The
boxplots given in figure 15b show the overall terrain ruggedness statistics of multi-source DEM at different scales. At higher spatial resolution (1m) more variability in terrain ruggedness has been observed. Whereas, at the moderate to low resolutions (10m, 30m and 90m) all the DEMs represents approximately similar terrain ruggedness distributions.

Figure 16 shows the topographic roughness error along the avalanche flow path. Terrain ruggedness along avalanche flow paths have been extracted from different DEMs and compared with reference DEM at different resolutions. It was observed that ALOS DEM has low RMSE and ME as ~18.7 and ~17.5 respectively whereas, SRTM has high RMSE and ME as ~153 and ~148 respectively as compared to other DEMs. Difference in topographic roughness is positive with respect to reference DEM, indicates that all the DEMS overestimate the terrain ruggedness at different spatial resolutions. Carto, ASTER and TOPO DEM has RMSE and MAE as 29.6 and 12, 45.2 and 42.9, 55.9 and 52.3, respectively.

5.2.4 Curvature:
Curvature is another avalanche influential factor. In this present paper, profile curvature have been created for all DEMs. Profile curvature provide indirectly the information of stress distribution along the hillside direction of avalanche prone area due to snow deposition. Based on the curvature of the topographic surface may be categorised into convex, concave or planar surface. Convex, plane and concave surfaces have positive, zero and negative curvature values, respectively. Nagarajan et al. (2014) has reported that balance of snowpack has been perceived on concave surfaces, while instability has been observed on convex surfaces. The curvature of MSP-10 avalanche site extracted from ADS is lies between -1189 to 715, whereas that of Carto, ALOS, TOPO, ASTER and SRTM ranges between -239 to 240, -31 to 17, -7 to 7.4, -11 to 16 and -4 to 3, respectively. Comparison of topographic curvature values of resampled DEMs at different spatial scale with respect to DEMs having
original cell size at that resolution is shown in figure 17. The MAE was observed between 2 to 17.1 for ALOS and ASTER data and 2 to 16.9 for SRTM for different resolutions. Also, at 10 m resolution all the DEMs have high values of MAE. Carto DEM has high MAE between 14.1 to 22.8 at all resolutions. Minimum MAE was observed at 30m and 90 m resolution.

Figure 18 shows the curvature error of along the avalanche flow path. Curvature along the avalanche flow path have been extracted using different source of DEMs and compared with reference DEM at different spatial resolution. It was observed that ALOS DEM has low RMSE as ~14.3, whereas, SRTM has high RMSE as ~21.4 as compared to other DEMs. Carto, ASTER and TOPO DEM has RMSE as ~25.2, ~18.8, and 18.9 respectively.

5.3 Analysis of Avalanche Simulation Parameters using Multisource DEM

Avalanche release area and debris flow extents are two most important parameters required for avalanche area identification and mapping. The list of required input parameters to estimate these avalanche related parameters is given in table 2. Both release area and flow extents primarily depend on the topographic parameters of the avalanche site, these parameters in turn derived from DEM (as discussed in the section 5.2.). The effect of DEM sources and scales (cell sizes) in mapping of avalanche release area and debris extant is analysed in this section.

5.3.1 Probable Avalanche Release Area:

To evaluate the effect of DEM sources in identification of avalanche release area, all elevation sources (ADS, Carto, ALOS TOPO, ASTER and SRTM DEM) at their original spatial resolution and also resampled at 5m spatial resolution were considered. The probable avalanche release area was estimated for each DEM using methodology presented in Buhler et al. (2013). Figure 19a show the variability in identification of PRA using different DEMs. The maximum release area values have been estimated for TOPO DEM and minimum for the
ADS DEM for MSP 10 avalanche site. The effect of resampling of the DEM cell sizes on release area size is presented in figure 19b. The result shows increase in the estimated release area using ADS DEM (at 5m) in comparison to release area estimated using ADS DEM (at 1m) and decrease in the PRA estimated using Carto, TOPO, ASTER and SRTM DEM (at 5m) in comparison to PRA estimated for these sources at their original resolutions respectively. Figure 20 illustrates detailed analysis of the avalanche release area count, size and misclassification variation at different spatial scale and using multi-source DEMs. It is observed that as the spatial scale increases from 1 m to 30 m release area count decreases, this may be due to merging of pixels and smoothing of the DEM (figure 20a). Large variation in release area has been observed between 1 m to 10 m scale, however above 10 m spatial scale all the DEMs have approximate same counts. Increase in release area size was observed as the spatial scale increases for all the DEMs and shown in figure 20b. Misclassification of release area is computed with respect to the release area estimated using ADS DEM at 1m resolution (figure 20c). The release area estimated using ADS and TOPO DEM are comparable at all the scales other than 1m. All the other DEMs (Carto, ALOS, ASTER and SRTM) underestimate the release area at 1m scale and overestimate it between 5m to 30m scale.

5.3.2 Avalanche Debris Extent:

In order to understand the effect of different elevation sources on avalanche debris flow extents, all multi-source DEMS (ADS, Carto, ALOS TOPO, ASTER and SRTM DEM) resampled at 5 m resolutions were considered. The flow extents were estimated for each DEM using the avalanche numerical flow simulation model developed by Christen et al. (2011). The model require DEM, avalanche release area, fracture height and model friction parameters as input. Release area has been estimated from reference DEM, fracture height
has been used 1.5 m and friction parameters were generated by the software using automated procedures after extensive terrain analysis of the DEM source provided to model. In present analysis all other input parameters were kept fixed except DEM source. The output parameters considered for analysis were debris extents in along (length) and across (width) the flow path, and maximum debris height of the flow. Other flow parameters (i.e., flow velocity and impact pressure etc.) were not considered in the present work. Figure 21 shows the comparisons of debris extents in run out area at derived from DEMs at 1m and 5m. The effect of elevation source is clearly visible in the flow pattern and extents of the avalanche debris. Figure 22(a-d) provided detailed analysis of the debris extents for different DEMs. The simulated debris extent in the direction of avalanche flow (figure 22a) shows the variation of ~80 m in the flow length derived from different DEMs. A significant difference of 55m was observed between the flow lengths simulations using ADS DEM at 1m and 5m resolution. The maximum along flow length 1204m for ASTER DEM and minimum 1120m for ADS DEM (1m) was observed. The debris width (across flow extents) has been observed 173 m and 300 m using reference DEM at 1m and 5m scale respectively (figure 22b). ALOS and ASTER DEM produces 373 m and 376 m debris width, which is very close to reference DEM at 5 m scale. However, Carto and TOPO DEM overestimate debris width estimate as ~394 m and 387 m respectively, whereas SRTM DEM underestimate as ~ 262 m as compared to reference DEM at 5m scale. The comparative analysis of the flow debris heights (figure 22c), show the maximum debris height 16m was found for ADS DEM simulation at 1m resolution, which is more than eight times higher than the debris height (2m) derived from SRTM DEM. The difference in the debris heights using ADS DEM at 1m and 5m was found 8m. The variability of avalanche debris height profiles of different DEMs along a common line along avalanche flow is illustrated in figure 22d. The large variations in debris extents (along, across and height) between ADS DEM at 1m and 5m resolution shows the
sensitivity of the DEM resolution in avalanche flow simulation.

6 Conclusions

Snow avalanches are common natural phenomenon in the snow-covered regions and become dangerous when they human being and infrastructure falls in way of avalanches. Avalanche occurrence depend on terrain and snow-meteorological parameters. Terrain topography is the most essential input in the process of avalanche hazard modelling, simulation and mapping. Also, the formation of the various avalanches and their movement through mountainous terrain is governed by the topographic parameters and their scales. However, these Digital Elevation Model (DEM) is the only source for deriving various topographic parameters.

In this paper an attempt has been made to estimate the suitable resolution and elevation data source for avalanche hazard mapping using different DEMs (i.e. SRTM (90m), ASTER (30m), TOPO (30m), ALOS (12.5m), CartoSat-1(10m) and Airborne Survey DEM (1m)) for the Manali Dhundi area, India. Initially, high resolution ADS80 DEM (reference DEM) elevations have been compared with ground collated elevation values using DGPS at 20 locations. The high coefficient of correlation (R2 =0.99) and low RMSE (~0.97 m) and MAE (~0.04 m) has been obtained between ADS DEM and DGPS elevation values. The minimum and maximum elevation error was observed -1.42 m and 1.36 m respectively. Further, high resolution airborne ADS80 DEM has been used to evaluate the open source DEMs for various topographic and avalanche related parameter estimation.

All the DEMs have been resampled at different scale of DEMs (1m, 10m, 30m and 90m) and terrain parameters (i.e., elevation, slope, terrain ruggedness and curvature) and avalanche simulation parameters (i.e., avalanche release area and debris extent) were derived and compared with reference DEM to estimate suitable scale and source of DEM. The salient deductions arising from this study are as follows:
- The high value of R² and minimum MAE was observed in ALOS and ASTER DEM at all resolution. At the 90 m resolution all DEMs have approximately equal MAE.

The MAE in ALOS and ASTER was observed 11.5 m and 31.4 m at 1 m spatial scale, whereas 29.3 m and 30.5 m at 10 m scale, 17.4 m at 30 m scale. However, TOPO DEM has large MAE at all the different scales. The minimum mean elevation difference is observed in ALOS DEM (~6 m) and maximum in TOPO DEM (~62 m).

ALOS DEM has low RMSE (~35 m) and ME (~32 m) in elevation as compared to other DEMs along the avalanche flow path. The high value of RMSE and ME is observed in TOPO DEM as ~149 m and ~134 m, respectively.

- The minimum and maximum MAE in slope values was found in ASTER (6.6° to 10.32°) and TOPO DEM (9.77° to 24.28°) as compared other DEMs at different resolutions. ASTER and TOPO has 9.88° and 24.28° MAE at 1 m spatial scale, whereas 10.32° and 12.09° at 10 m scale, 6.6° and 9.77° at 30 m scale. However, both ASTER and TOPO DEM has same spatial resolution (30m) but that show significant difference in the distribution of the slope values and their errors in study area. It was observed that ASTER DEM has lowest RMSE (10.1°) and ME (-2.8°) in slope values as compared to other DEMs. Carto, ALOS, TOPO and SRTM DEM has RMSE and MAE as 15.89° and -8.7°, 15.36° and -7.1°, 14.86° and -9.2°, 12.32° and -4.1°, respectively. At higher spatial resolution (1m) more slope variability has been observed among different DEMs.

- The minimum MAE (16 to 34) of topographic roughness was observed in ALOS data for all spatial scale up to 30m. In case of 90 m resolution all DEMs have large value of MAE as compared to other small scale DEMs. The MAE in ADS, ASTER, TOPO and SRTM was observed between 28 to 172, 28 to 155, 24 to 109 and 112 to 121 respectively at different DEMs resolutions. However, SRTM DEM has large MAE at
all the scales as compared to other DEMs at similar scales of other DEMs. At higher
spatial resolution (1m) more variability in terrain ruggedness has been observed for all
DEMs. Whereas, at the moderate to low resolutions (10m, 30m and 90m) all the
DEMs represents approximately similar terrain ruggedness distributions.

- The MAE in curvature was observed between 2 to 17.1 for ALOS and ASTER data
and 2 to 16.9 for SRTM for different resolutions. Also, at 10 m resolution all the
DEMs have high values of MAE. Carto DEM has high MAE between 14.1 to 22.8 at
all resolutions. Minimum MAE was observed at 30m and 90 m resolution. Curvature
variability was found decreasing with increasing cell sizes for all DEMs and
topographic features (convexities, concavities etc.) were well captured at moderate to
low resolution.

- The avalanche release area derived from different DEMs demonstrations that as the
spatial scale increases from 1 m to 30 m release area count decreases. This is because
merging of small release areas as a result of smoothing of DEM pixel variations due
to resampling. Large variation in the counts of release area has been observed
between 1 m to 10 m scale, however above 10 m spatial scale all the DEMs have
approximate same counts. Also, increase in release area size with increasing cell sizes
have been observed for all the DEMs. The release area estimated using ADS and
TOPO DEM are comparable at all the scales other than 1m. All the other DEMs
(Carto, ALOS, ASTER and SRTM) underestimate the release area at 1m scale and
overestimate it between 5m to 30m scale. High variability of the release area with
DEM cell size was observed for spatial resolution < 10m.

- The simulated debris flow length shows the variation of ~80 m for different DEMs. A
significant difference of 55m was observed between the flow lengths simulations
using ADS DEM at 1m and 5m resolution. The maximum along flow length 1204m
for ASTER DEM and minimum 1120m for ADS DEM (1m) was observed. The debris width (across flow extents) has been observed 173 m and 300 m using reference DEM at 1m and 5m scale respectively. ALOS and ASTER DEM produces 373 m and 376 m debris width. High variability in debris width is also observed for up to cell size of 5m for all DEMs. The maximum debris height 16m was found for ADS DEM simulation at 1m resolution, which is more than eight times of the debris height (2m) derived from SRTM DEM. The difference in the debris heights using ADS DEM at 1m at 5m was found 8m. The large variations in debris extents (along, across and height) between ADS DEM at 1m and 5m resolution exhibits the high sensitivity of the DEM resolutions in avalanche flow simulation.

In summary, among various DEMs (SRTM, ASTER, TOPO, ALOS, and CartoSat-1), ALOS and ASTER DEM provide equally reliable representation of actual topography and debris extent with respect to reference DEM. However, TOPO DEM provide good accuracy for calculation of release area as compared to other DEMs. Topographic parameters slope and ruggedness derived from ADS DEM at 5m to 10m resolution provide fairly good representation of avalanche terrain. Extraction of topographic curvature was found most suitable at ≥ 30m resolution for avalanche terrain. Most suitable scales for identification of avalanche release area and estimation of avalanche flow extent were observed between 5 to 10m. In the present work validation of the estimated release area and flow extent was carried out with the manually collected point observations from the field. Detailed field investigation using geospatial approach of data collection will be taken in future for detailed and multiple profile-based validation of these results.
Acknowledgements

The authors would like to thank Director DGRE for their continuous support and guidance during this work. Authors will also take this opportunity thank Agraj Upadhyay for providing support in numerical simulation of avalanches.

Author Contributions

Sanjay Kumar Dewali: Conceptualization, methodology, data analysis, software, writing – original draft, writing – review & editing. Kamal Jain: Supervision, writing – review & editing. Dhiraj Kumar Singh: Data analysis, field validation experimentation and editing of manuscript.

Funding

No additional funding was used for this work.

Ethics Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References


Jayappa, K.S., Markose, V.J., and Nagaraju, M. 2012. Identification of geomorphic signatures of neotectonic activity using DEM in the Precambrian Terrain of Western Ghats, India. In: International Archives of the Photogrammetry, Remote Sensing and...


Magesh, N.S., Jitheshlal, K.V., Chandrasekar, N., and Jini, K.V. 2013. Geographical information system-based morphometric analysis of Bharathapuzha river basin, Kerala,


### List of Tables

Table 1. Information about the remote sensing-based DEMs used in this study

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>DEM</th>
<th>Spatial Resolution</th>
<th>Source</th>
<th>Method/Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Airborne Survey</td>
<td>1m</td>
<td>DGRE</td>
<td>aerial photogrammetric</td>
</tr>
<tr>
<td>2</td>
<td>Cartosat-1</td>
<td>10m</td>
<td>DGRE, NRSC</td>
<td>Stereo pair based</td>
</tr>
<tr>
<td>3</td>
<td>ALOS</td>
<td>12.5m</td>
<td><a href="https://search.asf.alaska.edu/">https://search.asf.alaska.edu/</a></td>
<td>Stereo matching</td>
</tr>
<tr>
<td>4</td>
<td>ASTER</td>
<td>30m</td>
<td><a href="http://earthexplorer.usgs.gov">earthexplorer.usgs.gov</a></td>
<td>Stereo matching</td>
</tr>
<tr>
<td>5</td>
<td>TOPO</td>
<td>30m</td>
<td>DGRE</td>
<td>Toposheets based</td>
</tr>
<tr>
<td>6</td>
<td>SRTM</td>
<td>90m</td>
<td><a href="http://glcf.umbics.umd.edu">http://glcf.umbics.umd.edu</a></td>
<td>InSAR</td>
</tr>
</tbody>
</table>

Table 2. Input parameters required for avalanche flow simulation analysis

<table>
<thead>
<tr>
<th>Release Area</th>
<th>Debris Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sl No</td>
<td>Parameter</td>
</tr>
<tr>
<td>1</td>
<td>DEM</td>
</tr>
<tr>
<td>2</td>
<td>Forest Cover</td>
</tr>
<tr>
<td>3</td>
<td>Release Area</td>
</tr>
<tr>
<td>4</td>
<td>Forest Cover</td>
</tr>
<tr>
<td>6</td>
<td>Snow Density</td>
</tr>
</tbody>
</table>
List of Figures

**Figure 1**

- (a) Geographical location of Manali-Dhundi area,
- (b) Study area shown on the background imagery from Senrinal-2 image and DGPS measured GCPs are shown with green colour,
- (c) Avalanche occurrence data of study area during 1973–2017. The radius in the...
polar coordinate demonstrates the number of avalanches, and the angle indicates the years, and (d) enlarged view of avalanche site MSP-10 (yellow frame) shown on background of high resolution airborne image. (e) and (f) shows field photographs of DGPS survey performed over various locations.

Figure 2. Hillshade 3D view of DEMs with different spatial resolution (a) Airborne Survey, (b) Cartosat-1, (c) ALOS, (d) ASTER, (e) TOPO and SRTM.
Figure 3. Methodology adopted for present study
Figure 4. Comparison of elevation estimated from airborne ADS80 DEM and DGPS.

- Elevation
- Elevation Error

- $R^2 = 0.99$
- RMSE = 0.97 m
- MAE = 0.04 m
Figure 5. Boxplot of elevation values of different DEMs for the study area at original cell sizes.
Figure 6. Elevation Profiles along a common line of Multi-source DEMs at original cell sizes.
Figure 7
Figure 7. (a) Square grids with centre points over images of study area, (b) & (c) Histograms and Q-Q plots of the elevation values of different data sources and (d) scatter plots of the elevation values of different data sources with respect to reference ADS DEM.

Figure 8. Elevation variations over a common area of Multi-source DEMs.
Figure 9. Comparative analysis of elevation of DEMs (i.e., ADS, Carto, ALOS, TOPO, ASTER and SRTM) at different spatial resolutions (i.e. 1m, 10m, 30m and 90m) with respect to DEMs having original cell size at same resolution.
Figure 10
Figure 10 (a-f). Spatial distributions of elevation differences between multi-source DEMs at their original spatial resolutions and reference DEM resampled at same resolutions. Spatial elevation differences between DEMs (a) ADS – Carto at 10m, (b) ADS – ALOS at 12.5 m, (c) ADS – TOPO at 30 m, (d) ADS- ASTER at 30 m, (e) ADS-SRTM at 90 m, (f) Frequency distribution of the elevation differences (a) to (e).

Figure 11
Figure 11. Elevation error along the avalanche flow path of different DEMs compared with reference DEM at different DEMs resolution.

Figure 12 (a & b)
Figure 12(a). Comparative analysis of slope values of DEMs (i.e., ADS, Carto, ALOS, TOPO, ASTER and SRTM) at different spatial resolutions (i.e., 1m, 10m, 30m and 90m) with respect to DEMs having original cell size at same resolution.

Figure 12(b). Overall statistics of slope values of DEMs (i.e., ADS, Carto, ALOS, TOPO, ASTER and SRTM) at 1m, 10m, 30m and 90m resolution.

Figure 13
Figure 13 (a-f). Spatial distributions of slope differences between multi-source DEMs at their original spatial resolutions and reference DEM resampled at same resolutions. Spatial slope differences between DEMs (a) ADS – Carto at 10m, (b) ADS – ALOS at 12.5 m, (c) ADS – TOPO at 30 m, (d) ADS – ASTER at 30 m, (e) ADS-SRTM at 90 m, (f) Frequency distribution of the slope differences (a) to (e).

Figure 14
Figure 14. Slope error along the avalanche flow path of different DEMs compared with reference DEM at different DEMs resolution.
Figure 15(a). Comparative analysis of terrain roughness values of DEMs (i.e., ADS, Carto, ALOS, TOPO, ASTER and SRTM) at different spatial resolutions (i.e., 1m, 10m, 30m and 90m) with respect to DEMs having original cell size at same resolution.

Figure 15(b). Overall statistics of terrain ruggedness values of different DEMs (i.e., ADS, Carto, ALOS, TOPO, ASTER and SRTM) at 1m, 10m, 30m and 90m resolution.
Figure 16. Terrain roughness error along the avalanche flow path of different DEMs compared with reference DEM at different DEMs resolution.
Figure 17. Comparative analysis of curvature values of DEMs (i.e., ADS, Carto, ALOS, TOPO, ASTER and SRTM) at different spatial resolutions (i.e., 1m, 10m, 30m and 90m) with respect to DEMs having original cell size at same resolution.
Figure 18. Curvature error along the avalanche flow path using different source of DEMs and compared with reference DEM at different DEMs resolution.
Figure 19(a). Comparison of the PRA identified using different DEMs at original resolution.

Figure 19(b). Comparison of the PRA identified using different DEMs at 5m resolution.
Figure 20. Comparisons of (a) Avalanche release area count, (b) Size of release area and (c) release area misclassification using different DEMs at various spatial scale (1m, 5m, 10m, 20m and 30m) in comparison to release area estimated using ADS (1m).
Figure 21. Comparisons of DEMs derived debris extent at 1m and 5m.
Figure 22(a-d). Comparisons of DEMs derived debris extents, (a) along the flow path, (b) across the flow path and (c) maximum debris height and (d) Debris height profile along a common line of different DEMs.