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Use of LiDAR-derived DEM and a stream length-gradient index approach to investigation of landslides in Zagros Mountains, Iran

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ABSTRACT

This paper presents an approach to stream length-gradient index analysis to identify tectonic signatures. The graded profile of the Dez River in Zagros Mountains, Iran, indicates that the area has been tectonically disturbed, and it triggers landslide hazards. The high-gradient index shows that a steeper gradient could be potentially a signature for landslides identification. The digital surface models acquired by airborne LiDAR were used in this study to generate the HRDEM. Our result shows a great potential for improving landslide investigations by implementing stream length-gradient index derived from the HRDEM in conjunction with the landslide inventories data-set in the GIS environment. We also identified a correlation between the stream length-gradient index and the graded topographic profile with slopes and landslides. This empirical approach was verified by geodata analytics and landslide inventories data-set in conjunction with field observations. This study has identified the locations of high-gradient indices with susceptible to landslides.

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KEYWORDS

LiDAR; HRDEM; tectonic signature; stream length-gradient index; GIS

Background and introduction

In the Zagros Mountains, the mechanism of landslides are complex in geological-geomorphological activities. These activities have created an immature and rugged landscape that impose various natural hazards. A high slope can influence the stability of the region, particularly, with high tectonic activities. Also, the presence of active faults influences occurrence of landslides. Sometimes earthquakes are triggering landslides in this region. Thus, finding a logical relationship between slopes and tectonic geomorphologic signatures such as stream length-gradient index and graded topographic profile can suggest landslide susceptible areas. Moreover, the high rainfall and erosion in some rock types such as marls, calcareous and silt are the major concerns in the Zagros Mountains for instability. We have experienced catastrophic landslides to low magnitude of landslides in the form of rock falls, rock slides, debris flows and complex in the Zagros Mountains. Sometimes, a high density of lineaments and faults are controlling landslides in the region (Pirasteh, Safari, Pradhan and Attarzadeh, 2010). Thus, tectonic geomorphologic signatures are playing a significant role in landslide assessments.

Landslides are the movement of a mass of rock, debris or earth down an unstable slope (Highland et al. 2008; Farrokhnia et al. 2011; Seefelder et al. 2016; Pirasteh & Li *in press*). Definition of the landslide is diverse and reflects the complex nature of various disciplines, such as geology and

geomorphology (Ali et al. 2003a, 2003b; Ali & Pirasteh 2004). We consider landslides as a general term, and it is used to describe the downslope movement of soil and rock under the effects of gravity (Cruden 1991).

Landslide hazards can be investigated qualitatively or quantitatively. Many efforts have been made to investigate the causes and mechanisms of landslides using remote sensing data, GIS-driven techniques and statistical models (Carrara et al. 1991; Montgomery & Dietrich 1994; Guzzetti et al. 1999, 2012; Zhou et al. 2003; Yilmaz & Yildirim 2006; Ardizzone et al. (2007; and Schulz 2007; Yalcin 2008; Abellán et al. 2010; Derron & Jaboyedoff 2010; Yilmaz 2010; Goetz et al. 2011; Pirasteh, Pradhan, Rizvi 2011; Pirasteh, Pradhan, Safari 2011; Schicker & Moon 2012; Cavalli et al. 2013; Zare et al. 2013; Guan et al. 2014; Jebur et al. 2014; Lee et al. 2014; Su et al. 2015; Youssef et al. 2015; Ciampalini et al. 2016). Very few studies (Bull 2007; Hamdouni et al. 2010; Catani et al. 2013) have noted the role of tectonic geomorphology such as stream length-gradient index in landslide investigations. They suggested that the stream length-gradient index in river segments with higher landslide frequencies is associated with the slope instability and lithology in active tectonics structures.

One of remote sensing techniques that have been undergoing rapid developments for landslides investigations is Light Detection And Ranging (LiDAR). LiDAR can provide high-resolution point clouds of the topography and has demonstrated a great potential for monitoring landslide or rockfall displacements (McKean & Roering 2004; Ardizzone et al. 2007; Teza et al. 2007; Abellán et al. 2010). Also, much scholarly research in different aspects of image processing (Rau et al. 2011; Li et al. 2015a, 2015b; Pirasteh et al. 2015; Su et al. 2015) and natural hazards such as landslides can be found from Wu and Sidle (1995); Pack (1995); Pack et al. (1998); McKean and Roering (2003); Pack and Tarboton (2004); McKean and Roering (2004); Watts (2004); Schulz (2004); Van Den Eeckhaut et al. (2005); Su and Bork (2006); Glenn et al. (2006); Safaiee et al. (2010); Pradhan and Pirasteh (2010); Spaete et al. (2011); Schicker and Moon (2012); Guzzetti et al. (2012); Choi et al. (2012); Solaimani et al. (2013). An overview of the different applications of LiDAR techniques for landslide investigations was given in Jaboyedoff et al. (2012). They presented how LiDAR-derived HRDEMs can be used to investigate landslide hazards, including detection and characterisation of mass movements, modelling, hazard assessment and susceptibility mapping.

Nevertheless, most of the existing landslide studies in the Zagros Mountains have not been presented well due to the lack of detailed surface information in the region. They used aerial photographs, satellite images and DEM derived from topographic maps by using various statistical and deterministic approaches (Roberts 2008; Rajabi et al. 2011). Thus, this becomes a motivation to utilize the new LiDAR-derived HRDEMs to investigate landslides in this region.

This study attempts to take an advantage of the LiDAR-derived HRDEMs to improve the investigation of landslide hazards by assessing stream length-gradient index and graded topographic profile in the Zagros Mountains, southwest Iran (Figure 1). This study contributes the visual interpretation and tectonic geomorphology of geodata analytics in the ArcGIS 10.4 version software by utilising LiDAR-HRDEM. The objective of this research is to investigate the stream length-gradient index and graded topographic profile of the Dez River in conjunction with the landslide inventory data-set and field observations. We have presented how landslides are associating with various tectonic geomorphology, faults, folds and stream length-gradient index. We used the detailed information and the lineament map to improve landslide investigations. The point cloud data was used to extract the DEM derivatives in the GIS environment. We have digitally drawn the Dez River profile and determined the susceptibility of landslide hazards by using visual interpretation and empirical method. The performance of this study was validated by the existing landslide inventory data-set and several field observations.

Study area, geological and tectonic setting

The study area is situated in the Zagros Fold Belt (ZFB) of the southwest of Iran (Figure 1). It is bounded by Longitude 47° 58' 10.42"–49° 18' 50.63" E and Latitude 32° 21' 40.94"–34° 29' 10" N.

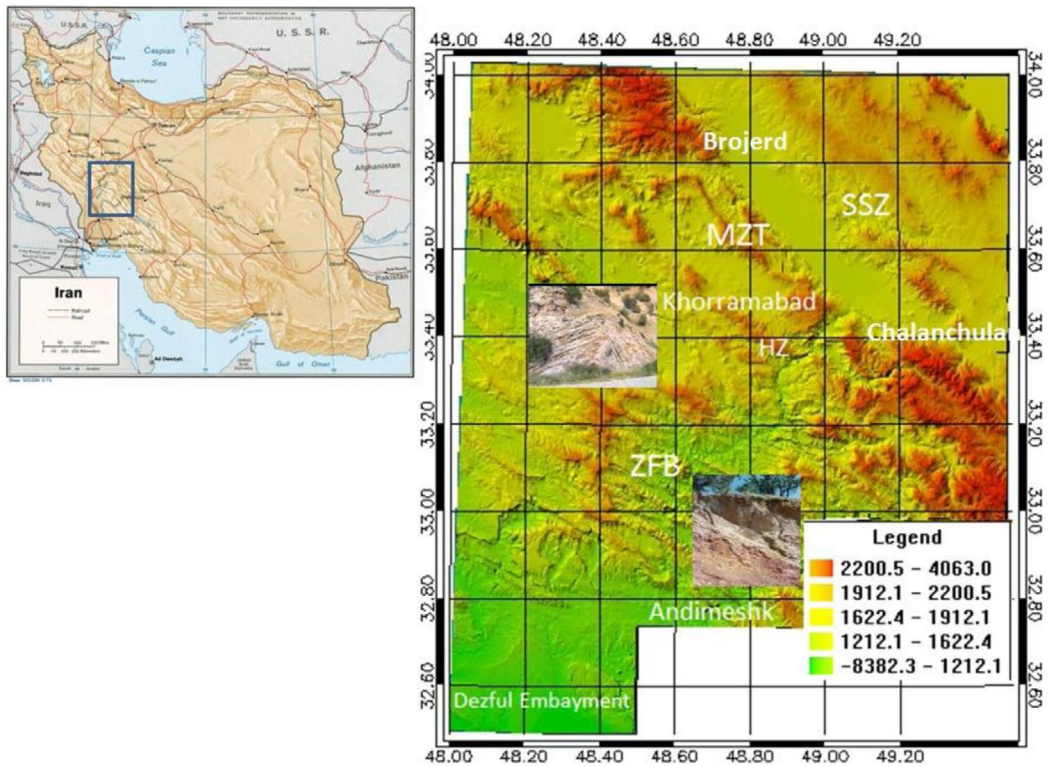


Figure 1. The study area is showing the Airborne LiDAR-derived DEM. ZFB: Zagros Folded Belt. HZ: High Zagros. MZT: Main Zagros Thrust. SSZ: Sanandaj Sirjan Zone.

Geologically, the study area consists of various lithological units. It ranges from Cretaceous age at the Sanandaj Sirjan Zone (SSZ) contact in the north-east (i.e. dominated by calcareous strata), and subrecent and recent age in the Zagros Structural Belt (ZSB) in the southern part of the study area. A generalized stratigraphic column (Figure 2) and the geological map (Figure 3) for the Zagros Simple Folded Belt are showing Cretaceous through Miocene strata grouped into four units according to relative resistance to erosion. Also, Figure 3 depicts spatial distribution of landslides inventory on the geological map of the study area in the GIS environment. The area is mostly dominated by calcareous Cretaceous dolomite, limestone, shale and marls in the north and evaporites (such as gypsum) and highly cemented conglomerate of the Pliocene Bakhtiari Formation in the south. The closure of the Zagros Basin during Cretaceous–Miocene time has generated diverse styles of folding and faulting. These structures, especially in the ZFB exhibit tight, NW-SE trending folds with closely spaced fracture systems interpret how it accelerates potential of landslides hazards occurrence. These types of geological settings have facilitated severe erosion (Figure 4) and the formation of rugged and immature topography and a closed drainage system.

In southwest Iran, the movement of the Arabian plate has been approximately NNE. It is resulting in closure, obduction and subduction of the Neo-Tethys beneath of the Iranian plate from about the Late Cretaceous onwards. Also, it formed roughly NW–SE trending Zagros fold mountains from about the Miocene onwards. However, the details of the collision are complex and have been accounted by some different models. While the detail of the sub-surface structural geology may be unresolved, the scenario at the surface using a HRDEM (Figure 5) and field checks (Figure 6) are relatively clear in this research. Development of folds in the ZSB is from the north-east to the south-west at the rate of

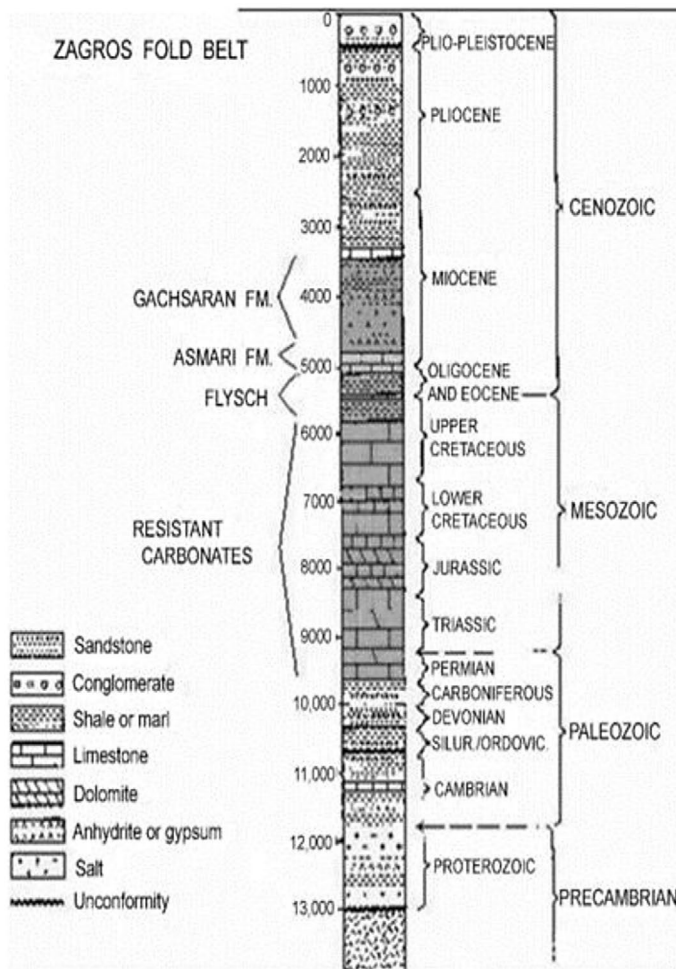


Figure 2. Generalized stratigraphic column of the study area (after Ali & Pirasteh 2004).

30 mm/yr (Berberian 1995), with a maximum fold crest uplift the rate of 1 cm/yr. Once fold growth has ceased, the landscape remains subject to uniform uplift at rate of 1 mm/yr due to crustal thickening at depth. Uplifting and folding are the two most important factors that are accelerating landslides in time. As the uplift is continuing, the drainage networks are adjusting and controlling the structure and lithology. Thus, it influences landslides in some parts of the area where the lineament density and slope are high.

Tectonic force is an impulsive event that occurs at the beginning of the geomorphic cycle and further influences landslides. Subsequently, geomorphic processes attack and degrade the topography and susceptibility of the landslide hazards. Since tectonic activities in the area has started during the Triassic and Late Cretaceous periods, the oldest geomorphic features have formed in the Zagros Mountains and resulted in the rugged topography. The effects of tectonic activities in the Zagros Mountains are more than those of sedimentation and the rate of erosion. Therefore, erosion may not have a significant contribution to changes in topography, landscape uplifting and landslides. The zone of rapid rock uplift had a steeper gradient, higher relief and higher gradient indices than the gentle topography zone (Burbank & Anderson 2001; Kirby & Whipple 2012). To emphasize the stream length-gradient

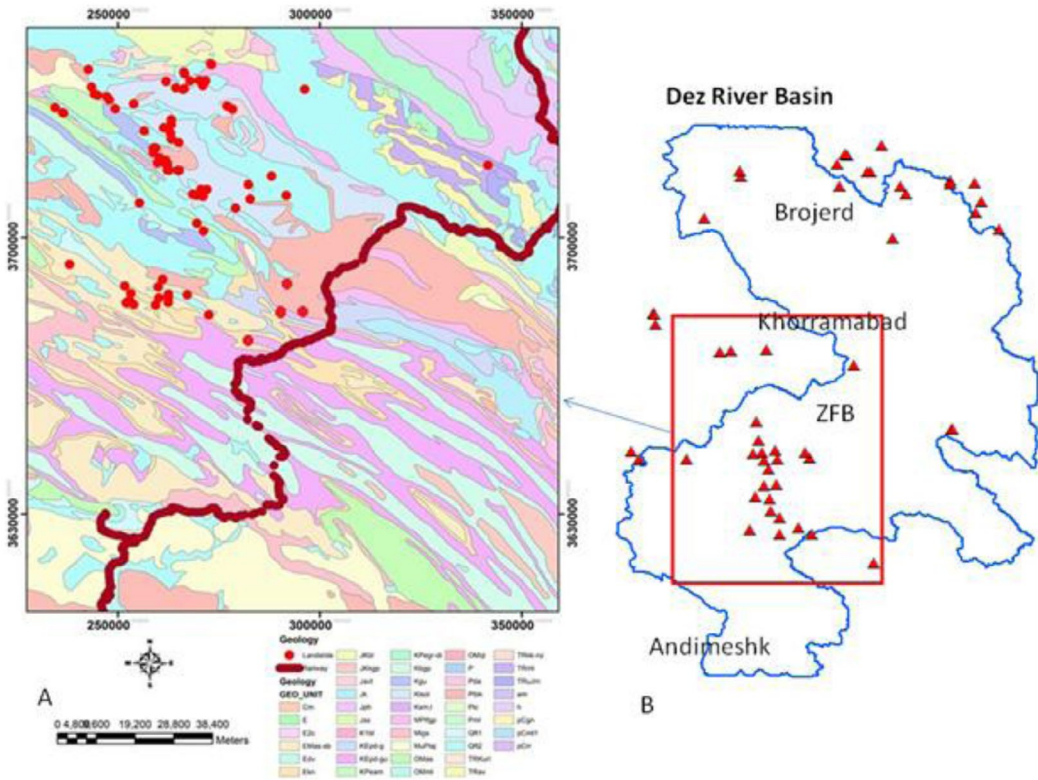


Figure 3. (A) New landslides identified in the Zagros Mountains and overlaid on the geological map of the study area in ZSB, Iran. (B) Landslide inventory data-set overlaid on the Dez River Basin.

index as one of the tectonic geomorphologic signatures on the landslide hazards recognition, we have compiled lineaments density map with the stream gradients of the Dez River profile derived from the HRDEMs (Figure 5). Nevertheless, a visual interpretation and geodata of stream length-gradient index analysis on the LiDAR-DEMs have contributed considerably to the investigation of landslides, and can deliver an improved method for the landslide susceptibility mapping. Now, the following section is describing the methodology of how HRDEM processed and stream-gradient indices are determined.

Methodology

Data characteristic and acquisition

In spatial analysis measurements, the HRDEM, slope, stream profile and river network of the ZSB were considered. The HRDEM of the ZSB is the most useful representation of terrain in the GIS for spatial analysis. An HRDEM is the raster representation, in which each grid cell records the elevation of the earth's surface, and reflects a view of terrain as a field of elevation values.

In this study, the acquisition of point cloud data over the ZSB was completed using a Leica ALS80-UP airborne LiDAR system on July 16, 2015. The data are in the digital form with x, y and z. The airborne LiDAR data-set consists first pulse returns. The fly altitude was 4200 m above ground with laser scanning swath width of 5000 m. The laser scan Field of View (FOV) set up for max 75°. This was up to 70 Hz (FOV dependent) scan rate and 24–25 kHz laser pulse rate, and 3 at 45 kHz laser returns for less than 30 cm RMSE absolute X, Y, Z positional accuracy. Airborne LiDAR specifications are depicted in Table 1. The approximate vertical tolerances were 0.05 m with average point density point of 0.8 points/m².



Figure 6. Field photo shows the development of folds and faults. (See Figure 1 for photo's location).

Table 1. Airborne LiDAR system specifications (After Cline et al. 2001).

Measuring frequency	24–25 kHz
Max. Operating altitude above ground	4200 m
Scanning frequency	70 Hz
Scanning angle	75° max

Processing of airborne LiDAR data

The point clouds with 3D coordinates of x, y and z from airborne LiDAR were used to generate the HRDEM. Since the most parts of the Zagros Mountains are covered by vegetation, the first step in our method is to remove the vegetation points from the raw point clouds that include terrain surface and vegetation. A semi-automated method was used to remove the noise and classify the objects allowed us to detect and interpret particular objects in the study area. Then the HRDEM is applied for further tectonic geomorphologic analysis, visual interpretation and landslide investigations. We extracted the bare-earth (i.e. segregating objects such as trees from the surface and extracting the terrain surface only).

The pre-processing technique has been applied to the LiDAR data to achieve the certain level of quality data before it is used for tectonic geomorphology analysis, visual interpretation and landslide investigations. This process has a direct impact on the quality of the DEM, visual interpretation, geodata analytics of stream length-gradient index and landslide investigations. During last decades, various solutions and algorithms for the classification of the LiDAR data were published (Glenn et al. 2006; Ardizzone et al. 2007; Derron & Jaboyedoff 2010; Spaete et al. 2011; Guan et al. 2014; Su et al. 2015; Ciampalini et al. 2016). The method was based on the surface interpolation (Pfeifer et al. 1998). The DEM was calculated based on the entire point set by adapting the influence of the individual input points. We used Hierarchical Robust Filtering (HRF) method and River Tool software to develop the HRDEM of the Zagros mountains. HRF method is originally designed for laser data in the vegetated and rugged topography areas such as the ZSB. This algorithm is embedded in the SCOP++ software.

The HRF involves four processing steps, including (1) thinning out, (2) filtering, (3) interpolating and (4) sorting out. In the raster-based thinning out step, a grid is laid over the complete data and one point is selected for each cell. In the filtering step, a DEM is computed based on a weighting function (Pfeifer et al. 1998), which is used to provide a low to high computational weighting for each cell. The weight function has a half of its maximum value (h is the half-width value) at h above g . These values determine the steepness of the weight function at a particular point. The cut off refers to ' t ' in the right tail the weight function (Figure 7). As for the interpolation, the DEM is derived from the current data-set by interpolation approach without differentiating data points. As for the sort out step, we define the distance from the calculated DEM by data points and three iterations. The classifying step has completed the filtering procedure. The major extension of the sort out step was to classify step. After HRF, the DEM was ready to use in the GIS environment for geodata of tectonic geomorphology analysis and visual interpretation to identify susceptible landslide prone areas. It was done based on the empirical approach in conjunction with the updated landslide inventory data-set and field observations.

Determining of stream length-gradient index in GIS

Tectonic activities have formed different geomorphic features on the Earth's surface. These features are signatures and insights to understand the tectonic activities of the Zagros Mountains. Sometimes landslides are influenced by tectonic activities and triggered by earthquakes. These signatures have shown that they can be good indicators to recognize landslides in an active tectonic region. There are various factors such as slope and lithology that cause a landslide. A high stream length-gradient index and a step-like graded profile can be found in high slopes and scarps with low resistance rock type such as sandstone, limestone and marls of Aghajari Formation, and evaporites of the Pliocene Bakhtiari Formation (i.e. ZFB). Thus, we can establish a logic interpretation of the correlation between stream length-gradient index and topographic graded profile with the slope and resistance of rock type for landslide recognitions.

We extract the stream length-gradient index and topographic graded profile of the ZFB. The HRDEM was used in the RiverTools 3.0, by which the river profiles, networks and stream length-gradient index are extracted for landslide investigations. The Dez River profile (Figure 8) was extracted from the HRDEM to represent the relationships between topography, slope and tectonic geomorphic features on the landslide assessments. This process was done by using channel profile function from Tools menu in the shaded relief windows of the Rivertools software. Then the stream length-gradient index (SL) was calculated.

The stream length-gradient index is a signature sensitive to analyse the reach scale variability of tectonic function, rock resistance and topography that have associated with landslides process. The Dez River which flows over the rocks and soils in the Zagros Mountains tend to attain equilibrium

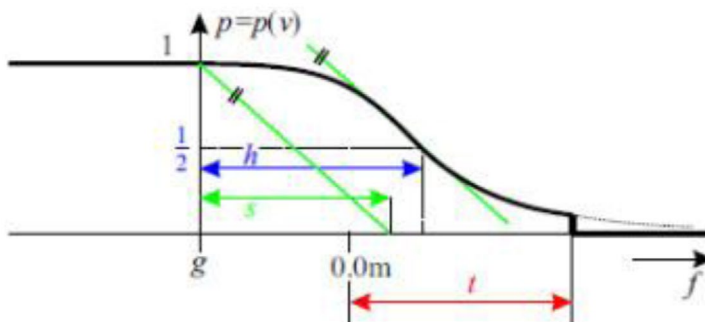


Figure 7. The weighting function (after Pfeifer et al. 1998).

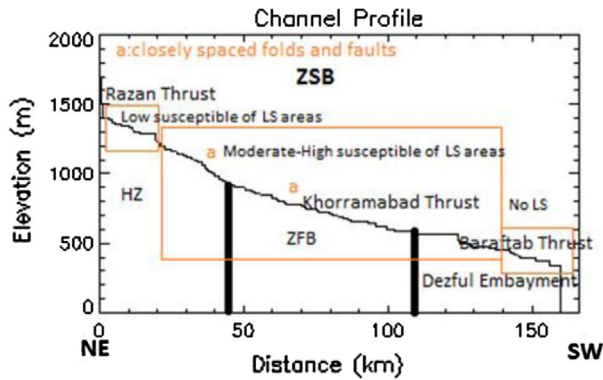


Figure 8. The Dez River step-like graded profile with about 165 km is showing landslide (LS) susceptible areas.

with distinct longitudinal profiles and hydraulic geometries (Bull 2007). We applied geospatial analysis on the stream length-gradient index in the GIS environment. By employing visual interpretation techniques, we estimate the relative tectonic activity in a river basin (Dar et al. 2014) that influences potential to landslides phenomena.

The stream length-gradient index (SL) is approximated by $SL = \Delta H / \Delta L \times L$ where L is the total river length from the midpoint of the chosen reach whose index is calculated, to the highest point on the channel. $\Delta H / \Delta L$ is channel slope or gradient of the reach in which ΔH is a change in elevation for a particular channel of the reach with respect to ΔL which represents the length of the reach. To calculate the stream length-gradient, we used the Dez River profile from Chalanchoolan police station near to Brojerd city (Figure 1) which is in contact of Sanandaj-Sirjan Zone (SSZ), Hight Zagros (HZ) and Zagros Fold Belt (ZFB). Figure 8 shows the Dez River step-like graded profile with a total stream length of about 165 km. The profile shows the high tectonic activity and landslide susceptible areas. The HZ topographic profile almost does not appear closely spaced folds and faults whereas in the ZFB due to the high tectonic activity, we experienced moderate to high potential of the susceptible landslide areas.

In the next step, the literature of tectonics and structural features of the study area such as structural map and lineament density map (James & Wynd 1965; Alavi 1994; Pirasteh et al. 2009; Safari et al. 2009; Pirasteh, Pradhan, Safari 2011, Pirasteh, Pradhan, Rizvi 2011; Rizvi et al. 2012) have been compiled and overlaid on the HR-DEM in the GIS software. The visualisation process in conjunction with landslide inventory data-set and image interpretation techniques of the HRDEM enhanced expression of the stream length-gradient index to recognize tectonic signatures for investigation of landslides.

The final stage of the process was to extract the Dez River network. It was done by using the river network function in the RiverTools 3.0 software. The morphometric parameters were converted to the ArcGIS format, in which the stream length-gradient index map was generated (see Figure 9). The step-like river profile of the study area has predicted to approach a graded profile. It indicates that the area has been tectonically disturbed and has associated with a high probability of landslides. The stream length-gradient index was deduced in each part of the profile (Figure 8). The stream length-gradient index map of the study area shows the tectonic zones in the ZSB and landslide prone areas (see Figure 8 to pinpoint the susceptible landslide areas). The high-gradient index on the map indicates the susceptible landslide areas.

Performance assessment

One of the fundamental steps in our approach for landslide recognition process is validation. In this study, the authentic process was applied to the reliability of the previous landslides inventory map,

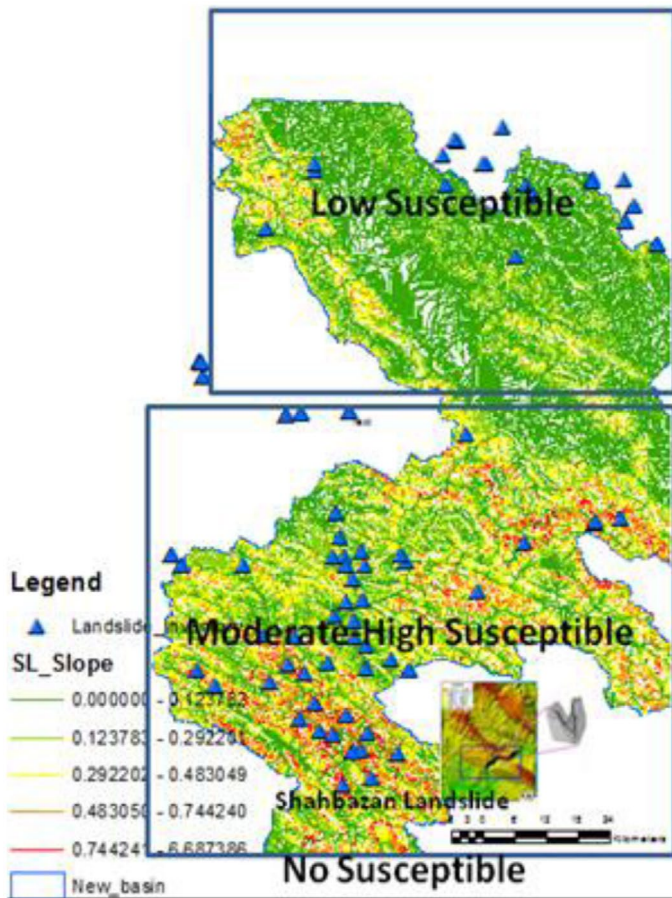


Figure 9. The stream length-gradient index map of the study area shows the tectonic zones in the ZSB and landslide prone areas (see Figure 8 to pinpoint the susceptible landslide areas). The high-gradient index on the map indicates the susceptible landslide areas.

geospatial locations of landslide data and parameters involve the landslide susceptibility prediction model used by the Geological Survey of Iran and the National Geoscience Database of Iran. The validity of thematic GIS layers was obtained through ground truth observations with the help of Global Positioning System (GPS). This method determined the performance of the output information derived from the geodata analytics of stream length-gradient index and visual interpretation of the LiDAR-derived HRDEMs. We assess that the proposed approach has improved the method of landslide investigations to support landslides susceptibility mapping. Moreover, the performance of detected landslide susceptible areas (Figures 8 and 9) are validated based on the empirical study and a field observation. An example of Shahbazan susceptible landslide visualisation has been pinpointed on the map (Figure 9).

Results

Although this study has not explored and discussed the detailed influencing factors of landslides, it shows how promising the LiDAR-derived HRDEMs and the stream length-gradient index are for landslide investigations in the Zagros Mountains. This study has identified one of the challenges, in which the LiDAR-derived HRDEMs were not able to delineate all the landslide boundaries within the landslide complexes due to its resolution limitation. However, the LiDAR-derived HRDEMs of the

study area obtained using available filtering algorithm and the RiverTools 3.0 software have shown the considerable improvement in landslide investigations. Moreover, our method has enhanced the landslide features that are in harmony with the stream length-gradient index and tectonic geomorphic signatures.

This study indicates that there is a direct relationship between slope instability, graded topographic profile and active tectonics in the Zagros Mountains as expressed by anomalous SL values on the map (Figure 9). Our analysis of the stream length-gradient index in the Dez River with the landslide inventory data-set and high landslide frequency, reveals that slope instability is associated with stream length-gradient index anomalies. This result corresponds to active tectonics structures in the Zagros Mountains with active faults and presence of earthquakes. However, we have exceptions for debris flows and rockfalls in conglomerates of Bakhtiyari Formation. This proposed approach is mainly for tectonic active region such as Zagros Mountains. Because, we have complex landslides and rock-falls that are mainly associated with not only upper fault blocks (where slope angles are increasing) but also with scarps and high angle slopes (i.e. sometimes about 90°).

The stream length-gradient index could be applied as an indicator to determine areas susceptible to landslides. Thus, it improves the landslides susceptibility mapping. The stream length-gradient index (SL) is a quantitative geomorphic parameter and has demonstrated to be a suitable tool for detecting stream-profiles related to active tectonics and surface processes such as landslides.

We have identified that after applying filtering and noise removal, the RiverTools software has allowed generating a high quality of the HRDEM of the Zagros Mountains. Second derivatives of the DEM such as slope, stream profile and drainage network have resulted in improving the visual interpretational method and processing data to map the spatial distribution of the SL index in the ArcGIS environment. This method uses stream length-gradient index as a tool to identify landslide prone areas. Figure 9 shows the landslide prone areas around the stream segments where the extreme index values occur.

An increase in stream length-gradient (SL) index values has resulted as a sign of elevated tectonic activity and it accelerates the potential for landslides. The study has demonstrated the existence of active deformation associated with landslides in the ZSB, as an indicator by steeper gradients in the zone of rapid rock uplift. High index values show that the steeper gradient and high tectonic activities associated with landslides in some areas that are mainly with thrusting and faulting like Main Zagros Thrust, Hoor Thrust, Chamsangar fault, Shahbazan strike-slip fault and Baraftab fault (Figure 5). The Dez River profile is indicating that the most active tectonic zone and landslide prone areas fall within the Folded Zagros (Figure 8). It interprets that the reduction in the gradient values towards the Dezful Embayment has low tectonic activities and landslides probability.

The different formations dominating various type of rocks like limestone and evaporates in the Gachsaran Formation, shale of Aghajari Formation, marls of Kashkan Formation, Cretaceous calcareous (i.e. contact of the Imbricate Zone and Zagros Fold Belt with Sanandaj-Sirjan Zone) may also approach the graded profile of the Dez River and they are associating with landslides. This study emphasizes that the ZSB has deformed and developed landslides not only because of the tectonic processes and uplift but also because of rugged and immature topography. A river profile of the study area is predicted to exhibit a graded profile, indicating that the area has been tectonically disturbed slowly, rather than rapidly and mostly occurrence of landslides depends on high tectonic activities.

The systematic stream-gradient map of the ZSB in the GIS environment shows the tectonic correlation and landslides. From the map (Figure 9), it is resulted that the Sanandaj-Sirjan Zone that exhibits 0 to 0.483 (i.e. SL slope) has low tectonic activity with no landslides visibility. It also reveals that the stream length-gradient index in the Zagros Fold Belt exhibits to 6.687. In other words, the area has a moderate to higher tectonic activity and have a great potential to landslides. This study shows that a low gradient index has a less susceptibility of landslides as compared to the high-gradient index. However, these tectonic activities in the Zagros Mountains have generated terraces and different type of landslides such as rock fall, flow debris and complex.

Discussion

LiDAR systems have been reviewed and discussed in Wehr and Lohr (1999) and Baltasvias (1999). A clear reference to an updated discussion is commented in Shan and Toth (2008) book. A brief review of LiDAR (and other remote sensing techniques) utilized in landslide studies is found in Prokop and Panholzer (2009) and SafeLand (2010).

The HRDEM of the study area has allowed detection of more informative landslide features than the coarse-resolution (e.g. 20 m or 30 m) DEMs derived from traditional techniques such as aerial photographs and topographic maps and other remote sensing techniques.

The challenge is that to get a flight permission from the Iranian authorities and it cannot be a good idea to use airborne LiDAR for study landslides and monitoring natural hazards from time to time. Moreover, the cost is high, and we cannot use airborne LiDAR at regular basis to monitor before and after an event. Thus, it is not possible to study landslides before and after the occurrence or expect to practice an early warning system using LiDAR techniques as we think of the future direction of landslide investigations in Iran. The area is a dense vegetation area and may obscure the morphology of landslides both in the field and in remotely sensed data. LiDAR data has processed to reveal the topography beneath vegetation (James et al. 2006). It has proven to be useful in identifying tectonic fault scarps, folds and to generate a high quality of the DEM derivatives such as river networks (Haugerud & Harding 2001; Haugerud et al. 2003; Sherrod et al. 2004), previously unmapped landslides and other geomorphic landforms.

The strength of using airborne LiDAR point cloud data as compared to other techniques is to generate the HRDEMs. Still, it becomes a challenge for the users to develop a software tool to detect landslides automatically. Our experience showed that it was also a challenging issue in the area (e.g. the ZSB) with a very steep terrain and cliffs due to lack of clear shots. Also, geological features, such as bedding and layering can sometimes be mistaken for instability as compared to field verification; it is always an essential component of the process.

Conclusion and recommendation

Steep hillslope and graded river profile are mostly susceptible for the landslide processes, but it is also affected by lithology and structure. Identification of the streams in hillslope with the help of DEM is also a difficult task. We recommend researchers to fit some analytical models with the help of existing landslide inventory data-set and stream gradient. These models will be different in different geological area. Thus, simply with the help of stream gradient alone, we cannot identify the landslide prone areas.

This study concluded that the zone of rapid rock uplift in the ZFB has a steeper gradient, higher gradient indices and probably high susceptible zones to landslides. This study derived that the HRDEM provided detailed information on the stream-profile metrics and improve landslide investigations. The stream-profile and stream length-gradient index map provide high potential insights to support susceptibility mapping with the limited resources in a very short time. In particular, our method showed a very promising approach to identify landslides in the Zagros Mountains where the method has thus far provided the best results. Our method has also showed potential to detect those landslides that directly reached the streambeds and whose magnitude and activity are high enough to generate stream perturbations in the Zagros Mountains.

Acknowledgements

We identified features that can provide us insights for landslide assessments. The high stream length-gradient indices in the study areas are determined in conjunction with field observations and landslide inventories available dataset. Remote sensing data such as an HRDEM is a remarkable element for extraction of the stream length-gradient index to assess landslides. Authors have used an empirical approach with geodata analytics in the GIS environment to estimate the landslide susceptible areas. This article is a part of the Ph.D. thesis that delivers an empirical approach in conjunction with the GIS analysis for landslides investigations from LiDAR point clouds.

Disclosure statement

No potential conflict of interest was reported by the authors.

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