World Journal of Environmental Biosciences

Available Online at: **www.environmentaljournals.org**

Volume 6, Supplementary: 26-36

ISSN 2277- 8047

Tectonic Geomorphology and Landslide Hazard Assessment of the Jajrood Watershed, Iran

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ABSTRACT

The geomorphic setting of the tectonically active area of Alborz Mountain is a result of complex interactions involving neo-tectonic movements and processes of erosion and deposition. Tectonic activity has significantly influenced the drainage system and the geomorphic situation in the area, leading to a high probability of the development of landslide, which is one of the major abrupt geological disasters in the region. Based on 10m-resolution DEM data, a total of 39 drainage basins were extracted using ArcGIS software. A total of 28 landslide valleys were visually interpreted from satellite images and published documents. Seven geomorphic indices were calculated for each basin including the relief amplitude, the hypsometric integral, the stream length gradient, the basin shape indices, the fractal dimension, the asymmetry factor, and the ratio of the valley floor width to the height. These geomorphic indices were divided into five classes and the ratio of the number of the landslide valleys to the number of the drainage basins for each geomorphic index was computed and analyzed for every class. Average class values of the seven indices were used to derive an index of relative active tectonics (IRAT). The ratio of the number of the landslide valleys to the number of the drainage basins was computed for every class of IRAT. The degree of probable risk level was then defined from the IRAT classes. Finally, the landslide hazard was evaluated for each drainage basin based on the combined effect of probable risk level and occurrence frequency of the landslides. The results showed an appropriate correspondence between IRAT classes and the ratio of the number of the landslide valleys to the number of the drainage basins .Approximately, 85% of the drainage basins with occurred landslide valleys are at a high risk level, while 33% of the drainage basins without occurred landslide valleys are at a high risk level. A comparison between the results of previous studies and the accuracy of these findings indicates that the basin topography created by rapid tectonic deformations is more favorable for landslide.According to Table 4, more than 85 percent of the slip intensity zones at Jajrood basin are in high and very high risk of landslides.

Keywords: *Alborz mountain area; Jajrood basin; Landslide; Geomorphic indices; IRAT.*

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INTRODUCTION

Landslidesare sudden natural disasters that often occur in mountainous regions. These Landslides are consisted of fully saturated mixtures of water, sediment and debris that can travel several kilometers, often in a series of surges, in mountainous torrents or across open hill slopes (Iverson, 1997). The higher the elevation of the mountain, the greater the static pressure of the landform, which enhances landfalls, earth slides, mountainous floods and landslides (Anbalagan and Singh, 1996).

Currently, hazard analysis of landslides and landslides is typically conducted by establishing a relationship between their cause and occurrence and assessing their hazard based on the relationship (Carrara, 1991; Mejia-Navarro et al., 1994; Chen and Wang, 2007). The factors used for hazard analysis of landslides and landslides fall into a number of categories, such as geomorphic, geological, land use/ land cover, and hydrological factors (Lee, 2005). Various approaches for hazard analysis of landslides and landslides have been developed by many researchers. These approaches include inventory analysis (Hewitt, 1998; Guzzetti, 2000), logistic regression (Lee, 2005; Chen and Wang, 2007; Mathew et al., 2007; Pradhan, 2010; Mousavi et al., 2011), multivariate statistical analysis models based on GIS and remote sensing techniques (Liu et al., 2004; Fourniadis et al., 2007; Lee and Choi, 2004; Manzo et al., 2012), and real-time landslide hazard management for early warning (Jakob et al., 2012).

Landslidesare erosive and accumulative processes in drainage basins for which active tectonics is a very important factor in the determination of the topographical characteristics of the drainage basin (Keller and Pinter, 2002a, 2002b). The occurrence of a landslide is mostly influenced by local topographical characteristics, active tectonics and rainfall. Although mainly controlled by tectonics (Mahmood and Gloaguen, 2012), the former two factors can provide the basis for occurrence of landslide (Wadge, 1994; Anbalagan and Singh, 1996).

Geomorphic indices have been used to assess the cause and occurrence of hazards (Lee, 2005). El Hamdouni et al. (2008) used six indices to compute the IRAT along the southwestern border of the Sierra Nevada in southern Spain and classified four classes of tectonic activity. These researchers concluded that relatively high potentials of active tectonics are associated with the indicative values of the IRAT. Mahmood and Gloaguen (2012) used seven geomorphic indices to compute the IRAT using GIS at the Hindu Kush, Karakorum, and Himalayas ranges. The indicative values of the IRAT are consistent with known uplift rates, landform characteristics and geology .Gao et al.(2013) used geomorphic indices such as the hypsometric integral and the stream length radiant index to infer and evaluate the recent uplift of the northeastern margin of the Tibetan Plateau. HI spatially corresponds to the hanging walls of thrust faults and is positively correlated with the leveling data. Alipoor et al. (2011) assessed active tectonics using geomorphic indices around the RudbarLorestan dam site in the High Zagros Belt (SW of Iran). Thus, strong tectonics can produce land-forms that may be favorable for landslides.

Assessment of landslide disasters often focuses on the regional/macro scale, and most researchers choose large-scale drainage basins as study objects for which the practical significance of the assessment results should be addressed (Lee, 2005; Chen and Wang, 2007;Pradhan, 2010; Mousavi et al., 2011). In this study, we have performed an analysis on a region that extends over the South Central Alborz mountain area in Iran. The study will discuss whether the susceptibility to a landslide hazard can be evaluated with parameters used for evaluating active tectonics; because topography of drainage basin created by rapid tectonics seems to be favorable for occurrence of landslide.The research method has consisted of extracting drainage basins from a DEM, calculating seven geomorphic indices, estimating IRAT, classifying IRAT levels,and determining the relationship between IRAT level and landslide distribution in the drainage basin.

2. Study area

The Jajrood basin to Latyan Dam is a region with an area of 69683 hectare which is located at the longitudes east of 51° ‹22′to 51°‹51′and latitude of north 35° ‹45′to 36 °‹50′. This basin, with more than 60 villages and permanent residents, is consisted of QasranRudbar and Lavasanat which are belonged to the government of Shemiranat city; Shemiranat is located about 10 Kilometer of North-eastern part of Tehran. This basin is limited to Lar dam form the north, to Karaj basin from the west and to the basin of the north of Tehran from the south.

The main river of this basin is named as Jajrood. This river is consisted of main branch of Garmabdar, Shemshak and Ahar at north which are joined at Fasham and Oshan, respectively; at the middle part, basin of Amameh River and subsidiary branches of Qochakroud have joined it and then it is poured into the lake of the dam. At the east side, basins of Kand, Afjeh and Varak rivers with some small subsidiary branches are flowing directly into the lake.This basin is consisted of sub-basins of Lavasan (Lavarak), Afjeh, Kand, Amameh, Garmabdar, Shemshak, Ab Meigon, Rodak and Qochak. The length of the basin is varying between 46 kilometers and its width between 14 to 28 kilometers from the place of the dam to the end of the basin.

Quaternary deposits are consisted mainly of alluvial channels, riverbasin, old and new alluvial terraces, alluvial fans, alluvial debris and present which have accounted for about 8% of the basin area (Karam et al., 56: 1389).From lithological perspective, the basin which has been studied has 26 different geological formations; much of the area is consisted of the Karaj, Fajan, Shemshak, Elika and HezarDareh formations which are mostly consisted of roar, pyroclastic rocks, shale, lime, conglomerate, sandstone and siltstones. The age of the oldest sediments of the basin has reached to pre-cambrian period and the age of the newest deposits has reached to quaternary period. Quaternary deposits of the basin are mostly consisted of alluvial river channel, new and old alluvial terraces, bomber fans, deposits and alluvial of the current age which forms 8 percent of the basin area (Karam et al, 1389:56). Geological and lithological characteristics of Jajrood basin and main fault systems such as Mosha fault – Fasham- and North Tehran fault in this area, as a part of the complicated tectonic system of the southern part of Alborz, has led to the fact that this basin is considered as an appropriate basin field for assessment of active tectonics criteria.

A large part of the study area is located at the elevation level of 1650 to 1750 meters with the slope of 10 to 25 percent at mountain and hilly with sensitive formations. Jajrood River, the main drainage of the region with the snow - rain regimen, is originated from the Shemshak Heights in the mountains of Alborz. The river is located in semi cold-arid climate. The mean annual precipitation in the region is about 4/265 mm, which evokes the Mediterranean regimen. Minimum and maximum temperature in the region is from -13 to 43 degrees. The speed of the dominant wind is 0.8 meter/second in the Latyan station and is direction is often to west.

The mountains located in the area are placed as bands across the north and some parts in the middle of the study area. These mountains are mostly poor from the soil coverage perspective. The mountains in the northern half have many rock outcrops in the form of rock mass and although having a lot of rock outcrops as the result of marl, salt and gypsum layers, the mountains in the middle part have very little vegetation.

The process of water erosion of the soil is high to very high, so in some areas, degraded lands (Bad Land) can be seen.

Jajrood River is located in the plains of clay sediment at the end of drainage basin of Jajrood and its alluvial fan form Morphological perspective. It has is very heavy texture and poor drainage. In the rainy seasons, it sometimes has the peat form and it can be seen as branches on the numerous water streams. These lands are now arid with incidental pasture with shrub and meadow cover of water-friendly vegetables.

In the margin of Jajrood River, landforms, relatively high mountains with arid use, low height mountainous lands with grassland use and small alluvial terraces which are limited between mountains with agricultural and garden use can be seen.

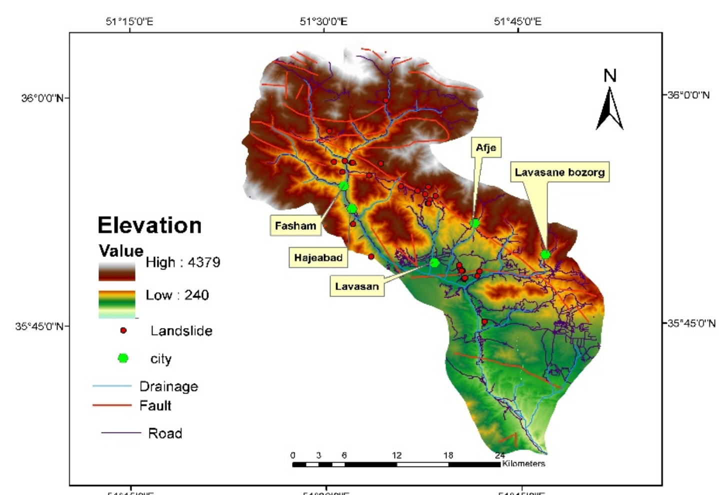


Fig. 1 Geographical setting of the study area.

The geomorphic setting in the Alborz mountain area is a result of complex interactions involving neo-tectonic movements and processes of erosion and deposition. The area experienced a strong neo-tectonic uplift, high rising and different tilting. These have created steep slopes, highly asymmetric valleys, elongated basins, V-shaped valleys, linearzed drainages, active mountain fronts, high channel gradients, and high hypsometric Integral in the area (Zhong et al, 2004).

METHODS

The DEM with a resolution of 10-m was used to extract drainage networks and drainage basins and calculate geomorphic indices using GIS techniques.Based on field investigationsand observation data reported in the landslide in Jajrood Basin, we visually interpreted and outlined 28 landslide valleys in 12drainage basins. The positions of landslide valleys are indicated by their central points as shown in Fig. 1.

Geomorphic indices are useful indicators for evaluating the influence of active tectonics. Calculated from remote sensing data (DEM and satellite/aerial imagery) using GIS, these indices can be used as a reconnaissance to detect tectonic activity such as uplift, incision, erosion, and slip, and provide a basis for analyzing probability of natural hazard occurrence (Khan et al., 2013). This method can provide useful information in the South CentralAlborz mountain area basin jajrood in Iran,where limited quantitative analyses of active tectonics were conducted.

In this study, assessment of landslide hazard was based on the drainage basins. First, drainage networks were extracted DEM, and thereafter, drainage basins were obtained using the ArcGIS ArcHydro Toolbox. For each drainage basin, seven geomorphic indices were calculated including the relief amplitude (RA), the hypsometric integral (HI), the stream length gradient (SL), the fractal dimension of drainage patterns (FD), the basin shape index (BS), the asymmetry factor (AF), and the ratio of valley floor width to height (VF).

Next, a composite index, IRAT, which is the arithmetic mean of the seven geomorphic indices, was obtained to assess the relative level of tectonic activity. The number of landslide valleys in each drainage basin was determined, and the IRAT value for each drainage basin was computed. The relationship between the IRAT class and the ratio of the number of the landslides to the number of the drainage basins was obtained and analyzed, and the probable risk level was defined by the IRAT classes.

Finally, the drainage basins were divided into two categories based on the occurrence of landslides. For drainage basins with landslide records, the degree of hazard occurrence probability for each drainage basin was estimated based on the combined effect of the probable risk level and the occurrence frequency of the landslides. Drainage basins without landslide records were classified according to their probable risk levels.

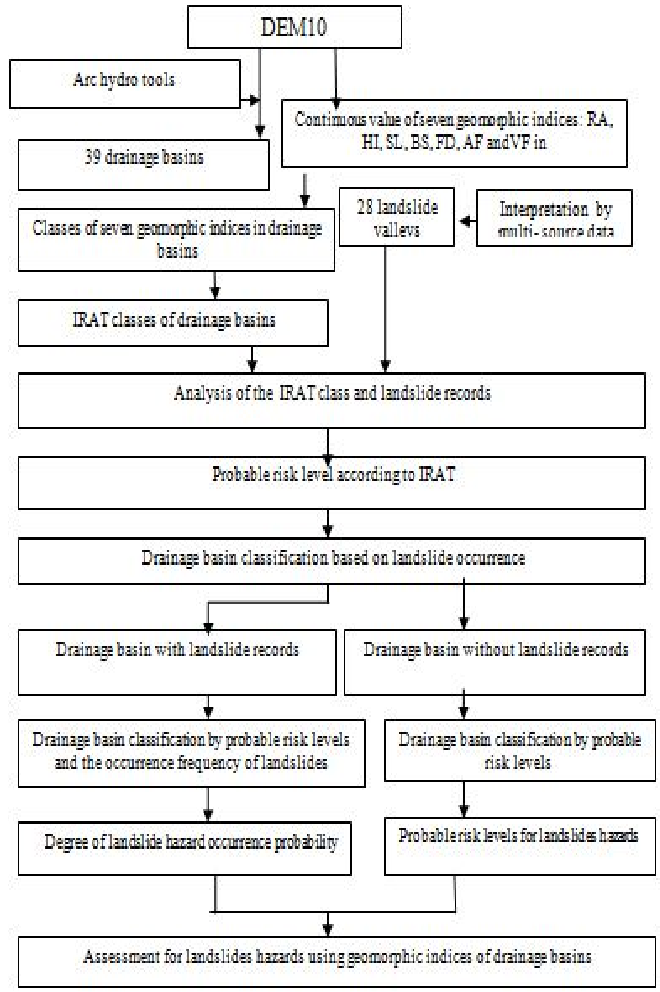


Fig. 2 Workflow of landslide hazard assessment.

4. Calculation of geomorphic indices

The geomorphic indices represent a quantitative approach for various geomorphic features such as the river channel, the long profile, the valley morphology, and the tectonically derived landforms (El Hamdouni et al., 2008). We analyzed the above-noted seven geomorphic indices in the study area and assigned them to different tectonic classes according to the range of values and their geological meanings .The seven indices were further grouped into four categories: 1)morphological index (RA), 2) tectonic uplift indices (HI and SL), 3) shape indices (FD and Bs), and 4) basin tilt indices (AF and VF).

4. 1. Morphological index

RA refers to the difference between the maximum and minimum elevations in an area such as a drainage basin (Whipple et al., 1999):

$$RA = hmax \_ hmin \qquad (1)$$

Where hmax and hmin are the maximum and minimum elevations (m) in a drainage basin, respectively.RA expresses the incision depth and the degree of surface denudation, which can be used to characterize the intensity of tectonic activity. Based on the digital geomorphic classification standards of China (Cheng et al., 2011), RA was classified into five classes: Class 1(RA b 70 m), 2 (70 m ≤ RA b 200 m), 3 (200 m ≤ RA b

500 m), 4 (500 m ≤ RA b 1000 m), and 5 (RA ≥ 1000 m) (Table 1).

4. 2. Tectonic uplift indices

HI is typically derived for a particular drainage basin as an index independent of the basin area. HI explains the distribution of elevations in a given landscape area, particularly a drainage basin (Strahler, 1952). The index is defined as the area below the hypsometric curve: thus it reflects the volume of a basin that has not been eroded. HI is approximated as (Pike and Wilson, 1971):

HI= (average elevation – min elevation)/(max elevation- min elevation) (2)

Where hmean is the mean elevation (m) of a drainage basin.

High HI values may suggest a younger landscape, possibly produced by active tectonics and generally corresponding to cases where majority of uplands have not been eroded. A high HI value could also result from a recent incision for a young geomorphic surface formed by deposition. Low values are related to older landscapes that have been significantly eroded and less impacted by recent active tectonics (Mahmood and Gloaguen, 2012). From the concept of theDivision erosion cycle theory (Davis, 1899), the HI values were divided into five classes: Class 1(HI b 0.3), 2 (0.3 ≤ HI b 0.4), 3 (0.4 ≤ HI b 0.5), 4 (0.5 ≤ HI b 0.6), and 5 (HI ≥ 0.6). The classification results are shown in Table 1.

SLwas defined by Hack (1973) to assess the influence of environmental variables on longitudinal stream profiles and to test whetherstreams had reached equilibrium. SL is an indicator to measure changesin a river profile, and in particular, it is very sensitive to changes in the river slope. Changes in SL are mainly influenced by tectonic activity, rock resistance to erosion, topographic characteristics and climatic factors (Hack, 1973). On the one hand, changes in the river gradient caused by local tectonic activities will increase the value of SL. On the other hand, flow through rock with strongly resistant to erosion and longterm differences in the erosion of adjacent regions will also steepen the river slope lead to an increased value of SL. The SL is computed using the equation:

SL= (ΔH/ ΔL) L (3)

Fig.3 Distribution of numerical classes of seven geomorphology indices for drainage basins. a) RA; b) HI; c) SL; d) FD; e) Bs; f) AF; g) Vf.

Where ΔH is the change in elevation (m), ΔL is the length of reach (m), and L is the horizontal length (m) from the drainage divide to the midpoint of the reach.

The value of SL was computed along the streams and rivers by drawing the "Hack profile" of each sub-basin and using Microsoft Excel to fit linear regression lines. The slope of the regression line corresponds to the SL index. The SL values in this paper were grouped into five classes based on Hack (1973):

Class 1 (SL b 25), 2 (25 ≤ SL b 75), 3 (75 ≤ SL b 200), 4 (200 ≤ SL b 400) and 5 (SL ≥ 400) (Table 1).

4. 3. Shape indices

FD is defined as a shape that in some way comprises parts similar to the whole (Guillermo et al., 2004; Dombradi et al., 2007; Gloaguen et al., 2007). The degree of complexity in a drainage network can be reflected by FD because the structure of the feature has characteristics of invariability of scale and self-similarity.

The box-counting method using a moving box of variable size was implemented on a binary image of the DEM-derived drainage network. This method interprets black drainage patterns as 1 and empty whitespace as 0, and counts the number of drainage pixels within the box (Skubalska-Rafajlowicz, 2005). FD is calculated as:

FD= Lim [logN(s)/ log (1/s)] (4)

Where N(S) is the number of boxes and S is the length of the box (m). The slope of the best fit line for a log–log plot of N(S) and 1/S is equal to FD.

The FD values were divided into five classes based on Guillemot al. (2004): Class 1 (FD ≥ 1.15), 2 (1.1 ≤ FD b 1.15), 3 (1.08 ≤ FD b 1.1), 4 (1.06 ≤ FD b 1.08), and 5 (FD b 1.06) (Table 1).

Bs represents the horizontal projection of a basin (Ramirez-Herrera, 1998), which is expressed as:

BS= BI/BW (5)

Where Lb is the length of a basin (m) measured from the headwaters to the mouth and WB is the width of a basin (m) measured at its widest cross section. The BS index can reflect the degree of active tectonic uplift. Normally, a high value of BS indicates a long and narrow drainage basin, for which the potential of tectonic activity is high. A low value reflects a nearly round basin and tectonic activity is weak (El Hamdouni et al., 2008). The values of the BS index are divided into five categories according to Ramirez-Herrera (1998): Class 1 (Bs b 0.2), 2 (0.2 ≤ Bs b 0.4), 3 (0.4 ≤ Bs b 0.8), 4 (0.8 ≤Bs b 1.2) and 5 (Bs ≥ 1.2) (Table 1).

4. 4. Basin tilt indices

AF is used for evaluating the tectonic tilting on a drainage basin scale (Hare and Gardner, 1985), and is sensitive to changes in inclination perpendicular to the flow direction. The method can be applied in a relatively large area. AF is defined as:

AF = |[(Ar/At)*100] – 50| (6)

Where Ar is the area (km2) of the basin on the right (looking downstream)of the main stream and At is the total area (km2) of the drainage basin.

AF has a threshold value of 50, which affects the active tectonics/ lithological control or differential erosion (El Hamdouni et al., 2008).When the value of AF is about 50, the basin is in a stable state with little or no tilt .When the value of AF is markedly greater or less than 50, the basin may be tilted, although geological conditions, such as changes in lithological structure may also cause such asymmetry.

The |AF–50| value was calculated and then divided into five classes according to Hare and Gardner (1985):

Class 1 (|AF–50| b 1), 2 (1 ≤ |AF–50| b 7.5), 3 (7.5 ≤ |AF–50| b 15), 4 (15 ≤ |AF–50| b 30) and 5 (|AF–50| ≥ 30) (Table 1).

VF is a geomorphic index that distinguishes between V-shaped and U-shaped valleys (Bull and McFadden, 1977). VF is defined as:

VF=2Vfw/[(Eid–Esc)+(Erd–Esc)] (7)

Where WVF is the width of the valley floor (m), ELD and ERD are the elevation (m) of the left- and right-hand valley divides (facing downstream), respectively, and ESC is the elevation of the valley floor (m). VF can reflect the level of tectonic activity: low values are associated with faster uplift and erosion and high values are with lower uplift rates. Different types of river valleys have different VF values. Generally, V-shaped valleys have relatively low values of VF whereas U-shaped valleys have relatively high values.

The VF values were divided into five classes based on Bull and McFadden (1977):

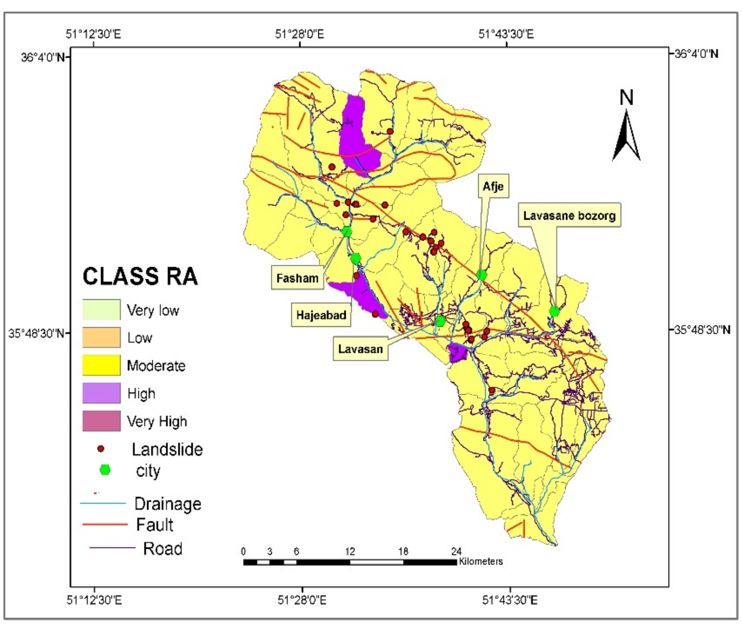
Class 1 (VF ≥ 5), 2 (2.5 ≤ VFB5), 3 (1 ≤ VFB 2.5), 4 (0.5 ≤ VFB 1) and 5 (VFB 0.5) (Table 1). McFadden (1977): Class 1 (VF ≥ 5), 2 (2.5 ≤ VFB 5), 3 (1 ≤ VFB 2.5), 4 (0.5 ≤ VF b 1) and 5 (VFB 0.5) (Table 1).

Table 1
Classification criteria of geomorphic indices representing active tectonics. RA: relief amplitude. HI: hypsometric integral. SL: stream length gradient. FD: fractal dimension of drainage patterns. Bs: basin shape index. AF: asymmetry factor. Vf: ratio of valley floor width to height.

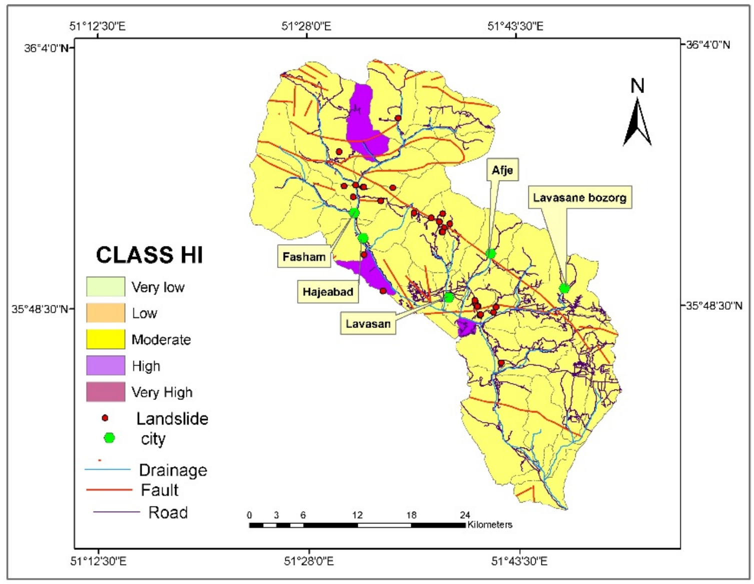
clas s	RA	HI	SL	FD	BS	AFI5 0I	F
1	<70	<0.3	<25	≥1.15	<0.2	<1	≥5
2	70-200	0.3-0.4	25-75	1.1-1.15	0.2-0.4	1-7.5	2.5-5
3	200-500	0.4-0.5	75-200	1.08-1.1	0.4-0.8	7.5-15	1.2.5
4	500-1000	0.5-0.6	200-400	1.06-1.08	0.8-1.2	15-30	.5-1
5	≥1000	≥0.6	≥400	< 1.06	≥1.2	≥30	<.5

Table 2
Number of the drainage basins for each class of the geomorphic indices. RA: relief amplitude. HI: hypsometric integral. SL: stream length gradient. FD: fractal dimension of drainage patterns. Bs: basin shape index. AF: asymmetry factor. Vf: ratio of valley floor width to height.

class	RA	HI	SL	FD	BS	AF-50II	VF
1	0	0	0	1	27	0	1
2	0	0	1	0	9	8	0
3	2	36	3	0	3	18	8
4	8	3	19	0	0	10	4
5	29	0	16	38	0	3	26



a)



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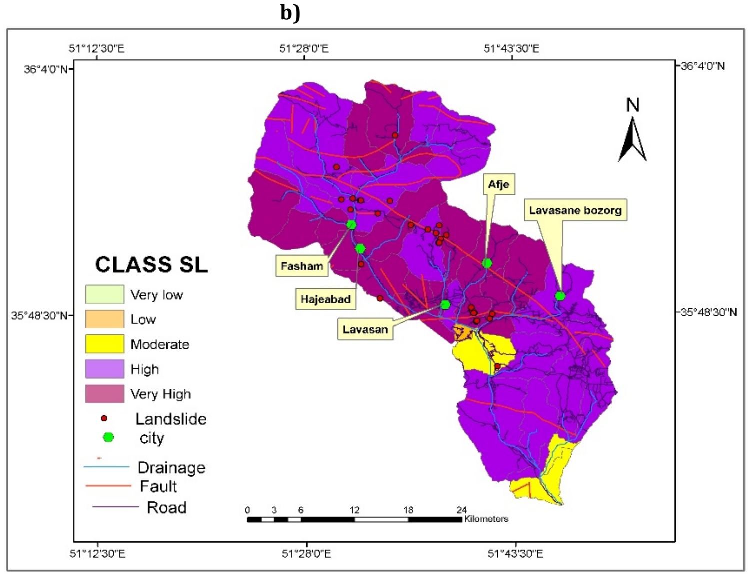

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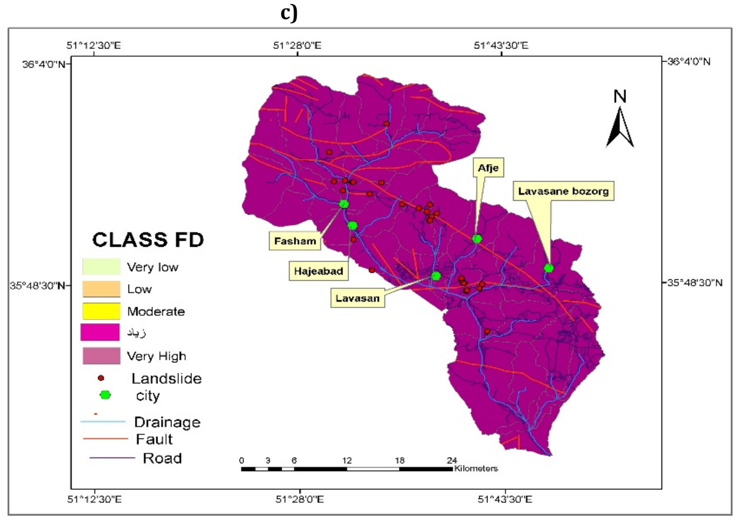

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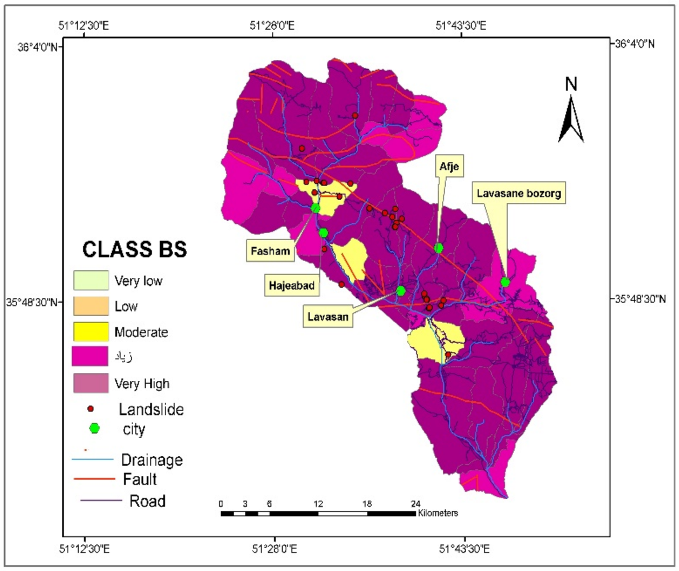

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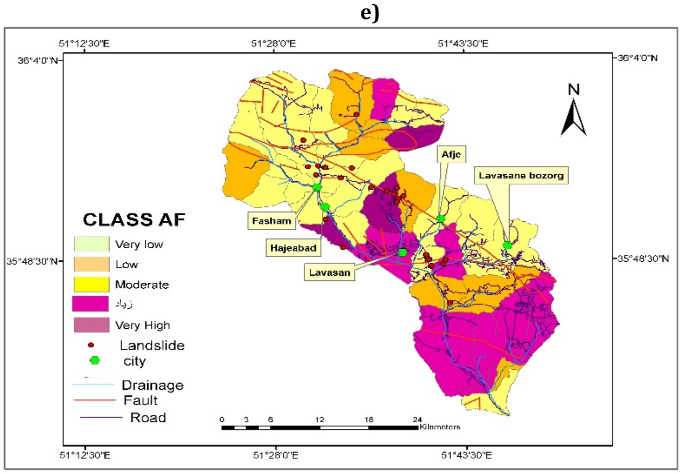

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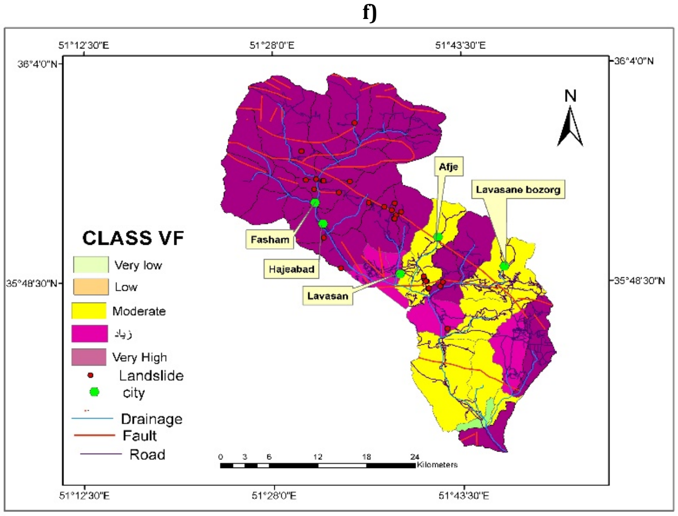


g)

4.4. Calculation of IRAT

Some previous studies used a combination of two or more geomorphologic indices to obtain semi-quantitative information regarding the relative tectonic activity of a mountain range (Bull and McFadden, 1977; Silva et al., 2003; El Hamdouni et al., 2008). The use of the seven geomorphic indices mentioned above, as well as IRAT, exhibits tectonic activity zones in the study area. We have summarized the classification criteria from previous research results (Strahler, 1952; Bull and McFadden, 1977; Molnar and England, 1990; Silva et al., 2003; Dehbozorgiet al., 2010). Based on the 28 landslide valleys within the Jajrood basin area and the geomorphic significance of the seven geomorphic indices, the classification criteria for each geomorphic index was redefined (Table 1). To obtain more precise results, the seven indices were divided into five classes, and each class was assigned a weighting value. These classes were then summed and averaged to obtain an IRAT over the entire study area. IRAT is defined as:

$$IRAT = (RA+HI+SL+FD+BS+AF+VF)/7 \qquad (8)$$

Such an arithmetic mean has been found useful in differentiating tectonically active areas (El Hamdouni et al., 2008; Dehbozorgi et al., 2010; Mahmood and Gloaguen, 2012).

RESULTS

5.1. Geomorphic indices

5.1.1. RA

The RA values in the study area range from 330 to 2190 m, with a mean of 1359.4 m. The drainage basin numbers for each RA class is shown in Table 2. Class 5 covers the largest area in the basin (74.36% of the entire basin) followed by Class 4 (21.51%) and Class 3 (4.13%).

The distribution of RA classes in the study area is shown in Fig. 3(a). Class 5 is mainly distributed in the steep slope area of the mountains, which are characterized by less vegetation coverage due to relatively frequent anthropogenic activities. Class 4 is mainly distributed in the inter-mountain area with dense land cover and relatively few anthropogenic activities. Class 3 is primarily distributed in low and gentle hilly areas.

5.1.2. HI

The HI values in the study area range from 0.491 to 0.501. The drainage basin numbers for each HI class (Table 2) shows that 92.3% of the drainage basins have HI between 0.4 and 0.5. Drainage basins with HI between 0.5 and 0.6 are 7.7%, of the total area.

The distribution of HI classes is shown in Fig. 3b Classes 3 and 4 are primarily distributed in the inter-mountain area with high to medium relief, steep slope gradients and dense vegetation.

5.1.3. SL

The number of the drainage basins with SL values higher than >400 accounts for 44.4% of the total area and values between 200-400 accounts for 48.7% and values between 75-200 accounts for 6.9%. The drainage basin numbers for each SL class is listed in Table 2. Each SL class is almost evenly distributed in terms of the number of basins.

5.1.4. FD

The highest value of FD within the study area is 0.402. The number of drainage basins for each FD class is described in Table 2. Class 5 covers the largest area in the basins (97.4%), followed by Class 1 (2.6%).

Fig. 3d shows the distribution of FD classes in the study area.

5. 1. 5. BS

The number of drainage basins for each BS class is listed in Table 2. The primarily BS class is Class 1 (69.2%), followed by Classes 2 (23%) and 3 (7.8%).

The distribution of BS classes in the study area is shown in Fig. 3(e) The three main classes (1, 2 and 3) are primarily distributed in the kernel area of the mountain. Most drainage basins are along the flow direction, indicating that these drainage basins deviate from the steady status.

5.1.6. AF

The number of drainage basins for each AF class is listed in Table 2. The primarily AF class is Class 3 (40.1%), followed by Classes 4 (25.6%) and 2 (20.5%) and 5 (13.8%).

The distribution of AF classes is shown in Fig. 3f Class 3 is widely distributed, indicating that the drainage basins have nearly symmetrical shapes.

5.1.7. VF

The VF values in the study area range from 0.05 to 9.98. The number of drainage basins for each VF class is shown in Table 2, and the distribution of the VF classes is shown in Fig. 3g.

5.2. IRAT

The ratio of the number of the landslide valleys to drainage basins for each geomorphic index (Table 3) shows that the ratio increases along with the increase of class. To use the geomorphic indices comprehensively, the IRAT value was computed based on Eq. (8) (Fig. 4). The IRAT values have a right-skewed tendency, indicating that the study area had a relatively strong neo-tectonic process during the Quaternary.

The IRAT values range from 0.64 to 5.79 with a mean of 2.63 and standard deviation of 1.07 indicating relatively active tectonics. The relatively low standard deviation reflects that tectonic activities do not vary significantly over the study area.

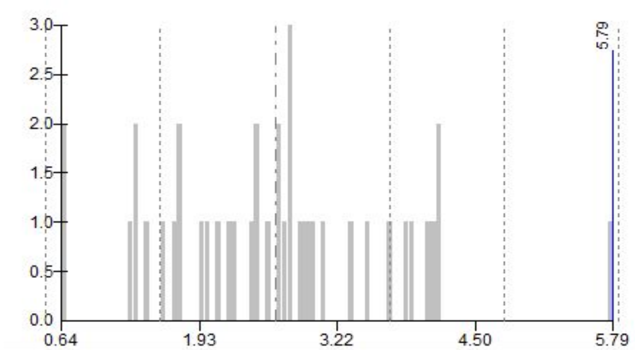
Based on IRAT, the 39 drainage basins in the study area were divided into five classes using the natural breaks method in ArcGIS: Class 1 with IRAT 0.64-1.45, 2 with 1.46-2.24, 3 with 2.25-3.07, 4 with 3.3.08-4.15, and 5 with 4.16-5.79 (Table 4, Fig. 5). Class 3 has 14 drainage basins and 8 landslide valleys, and Class 4 has 9 drainage basins and 17 landslide valleys approximately 2 landslide valleys per drainage basin5 and 1.89 landslide valleys per drainage basin4. For the lower classes, the number and relative frequency of landslide valleys evidently decrease.

High IRAT values occur in the northernhalf of the mountain district having steep slopes, high to medium relief, severe erosion, and dense faults. The moderate class is mainly distributed in the margin of the mountain districts having medium to lower life, slightly tilted slopes, sparse vegetation and intensive human activity. The lower class is primarily distributed around the Latyan Dam, which lies on the boundary between mountains and plains, and has gentle slopes, low relief, and fewer faults.

Table 3

Ratio of the number of landslide valleys to the number of the drainage basins for each class of the geomorphic indices. RA: relief amplitude. HI: hypsometric integral. SL: stream length gradient. FD: fractal dimension of drainage patterns. Bs: basin shape index. AF: asymmetry factor. Vf : ratio of valley floor width to height.

class	RA	HI	SL	FD	BS	AF-50II	VF
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0.5	0
3	0	0.75	0.33	0	1.33	0.89	0.75
4	0	0.33	0.68	0	0.11	0.2	0.25
5	0.97	0	0.88	0.71	0.85	2	0.81



IRAT value

Fig.4 Frequency distribution of the IRAT values

5.3. Assessment of landslide hazard probability

The IRAT classes have a close relationship with the occurrence probability of landslides (Table 4). In the study area, 12 drainage basins have records of landslide events. Therefore, the drainage basins can be divided into two types: landslide drainage basins and non- landslide drainage basins .We made assessment for each type.

Table 4

Numbers and ratios of drainage basins and debris landslides for different IRAT classes.

Class	Value	Drainage basins	Landslide	Landslide to drainage basin ratio
1	0.64- 1.47	6	0	0
2	1.48-2.24	9	1	0.11
3	2.25-3.07	14	8	0.57
4	3.08-4.15	9	17	0.89
5	4.16-5.8	1	2	2

5.3.1. Assessment of landslide drainage basins

The drainage basins in which landslides have occurred were divided into four classes based on the frequency of landslides: high frequency (≥6), medium (3–5), low (2), and very low (1) (Table 5).

In Table 5, among all the 12 landslide drainage basins, about 93% are distributed in the high and very high degrees of probable risk level. The degree of the landslide hazard occurrence probability increases along with the increase in the probable risk level.

The distribution of the degree of the landslide hazard occurrence probability is shown in Fig. 6. The degree of the landslide hazard occurrence probability is generally high all over the drainage basins. Areas with much higher probability degrees are primarily distributed in the northern District and the central area.

Table 5
Number of landslide drainage basins (left side of slash) and degree of the hazard occurrence probability (right side) at different frequencies and probable risk levels.

	Probable risk level				
Frequency	Very low	low	Moderate	High	Very High
6>	0	0	0	0	1.5
3-5	0	0	0	3.4	0
2	0	0	0	1.3	2.4
1	0	0	1.2	2.3	2.4

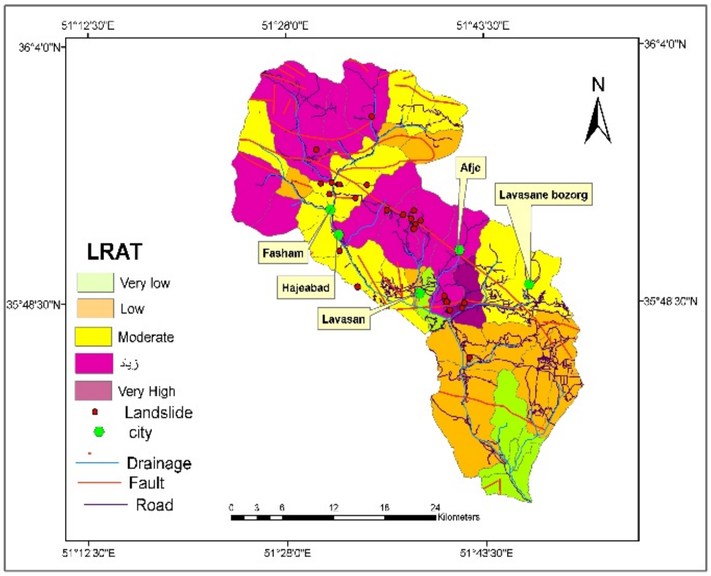


Fig.5 Distribution of IRAT classes for drainage basins.

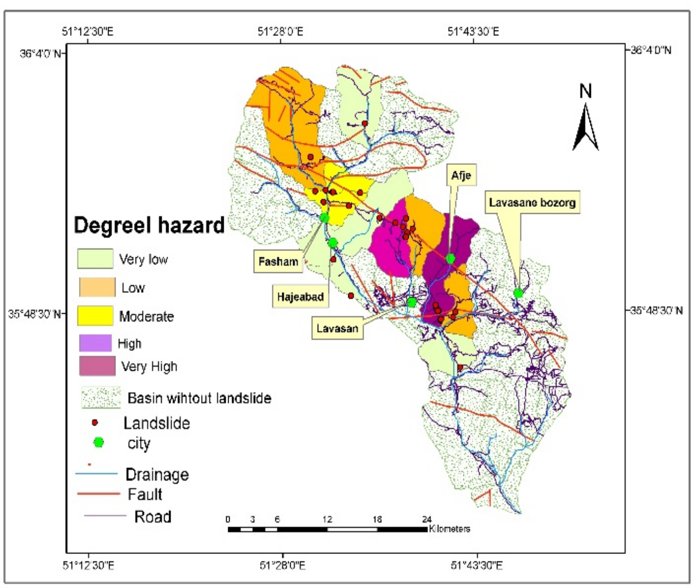


Fig.6 Degree of landslide hazard occurrence probability for drainage basins.

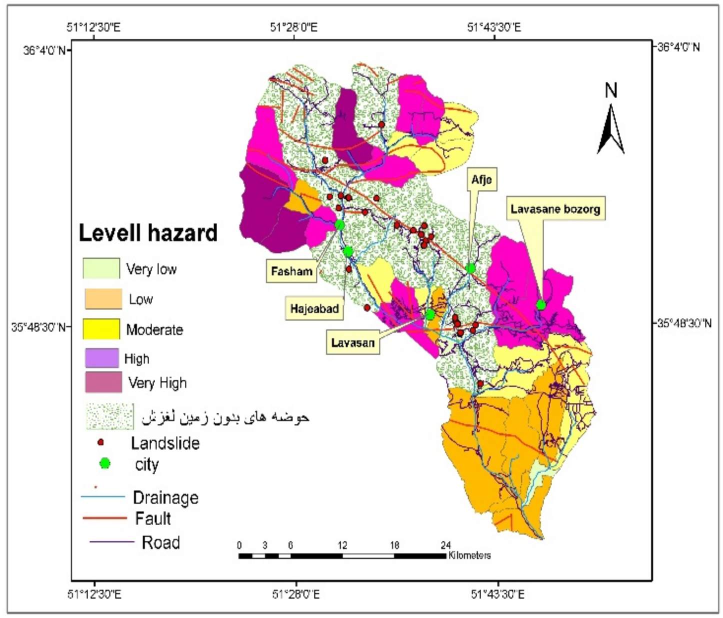


Fig .7 Distribution of probable risk levels for no landslide drainage basins

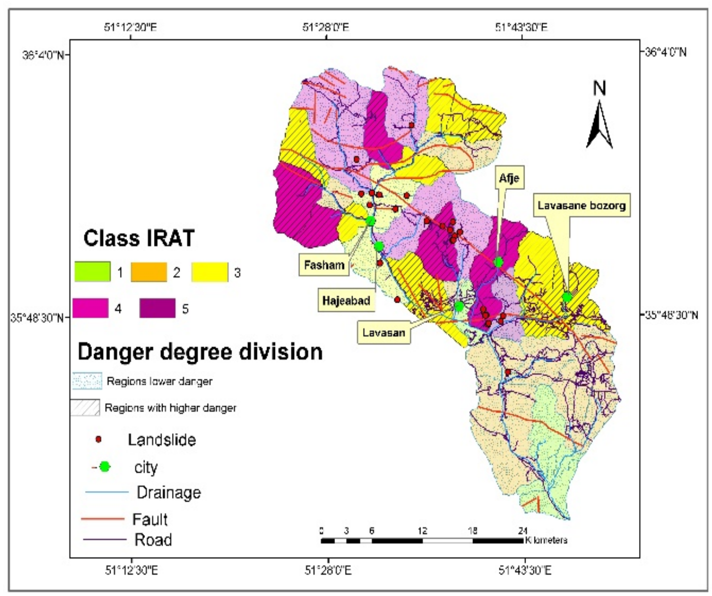


Fig.8 Comparison between the IRAT classes from this research and the danger degree
Divisions, based on Zhong et al. (2004).

5.3.2. Assessment of no landslide drainage basins

The drainage basins in which landslide did not occur was divided into five classes based on the probable risk level. The number of the no landslide drainage basins at the probable risk levels of very low, low, moderate, high and very high is. Of the 27 no landslide drainage basins, approximately 33% are distributed at the high and very high risk levels.

The distribution of no landslide drainage basins at different probable risk levels is shown in Fig. 7. The high level region is mainly distributed in north and northwestern, the central part of area in the basin, and the low level region is mainly distributed in the south and south eastern area around dam.

DISCUSSION

Based on the values of these indices, Zhong et al. (2004) identified zones of different dangerous degrees of landslide hazards in the JAJROOD Basin: higher danger zones, lower danger zones and non danger zones. Fig. 8 shows the distribution of the three zones and the IRAT values. The higher danger zones are mainly distributed in the Northern and central areas Basin. The regions with IRAT Classes 4 and 5 include 19 landslide of 28 landslide . The coincidence degree of the two results is high .This high coincidence confirms that IRAT can well represent the levels of landslide hazards.

The magnitude of a landslide hazard is affected by many factors. Therefore, Zhong et al. (2004) considered not only topography but also rainfall and lithology. However, geomorphic analysis is an essential basis for evaluating the occurrence of landslide hazards. For example, on the south flank of the Santa Ynez Range in southern California, USA, the morphologic conditions of drainage systems have provided channels dominated by landslides (Keller et al., 2015). Although the geomorphic conditions representing tectonic activities cannot fully confirm the occurrence of landslide, they may indicate drainage basins highly prone to hydro-geomorphic hazards including landslide (Khan et al., 2013).

CONCLUSIONS

Using a 10-m-resolution DEM, 39 drainage basins were extracted in the Jajrood Basin and seven geomorphic indices for the basins were computed. The IRAT value was computed as the arithmetic mean of the seven indices. IRAT is an indicator of the intensity of active tectonics. We also identified valleys where landslide occurred, and compared the number of the landslide valleys and the number of drainage basins with different classes of IRAT. According to Table 4, more than 85 percent of the basins with Jajrood slip intensity zones High and very high risks of landslides are located. The ratio increases with the increase of the class.

Drainage basins with higher IRAT values also correspond well to the higher danger zones of landslide identified by Zhong et al. (2004). Moreover, such basins often have records of past landslide events. These results indicate that the geomorphic conditions provided by tectonic activity are important basis for landslide hazards, although other factors also affect the occurrence of landslide.

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