



Quantitative analysis of relative active tectonics using geomorphic indices in Band-Golestan basin, northeastern Iran

Maliheh Pourali¹ · Reza Hoseynzadeh¹ · Morteza Akbari²

Received: 30 August 2019 / Revised: 3 November 2019 / Accepted: 11 November 2019
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Abstract Investigation of geomorphic indices is a useful approach to identify the specific characteristics of active tectonics in each region. In this study, five geomorphic indices including stream length-gradient index, basin asymmetry, hypsometric integral, ratio of valley-floor width, and index of basin shape were estimated to assess relative active tectonics in the Band-Golestan basin, as a part of Binaloud mountainous zone, located in northeastern Iran. This region includes several faults, formed mainly by contact, fraction, and re-crystallization processes between shale and sandstone rocks. An average index of the active tectonics was produced to categorize the intensity classes of tectonic activity of the study area. According to the mean values of indices, the whole basin has active or semi-active tectonics. After that, the overall index of Iat with a value of 1.88 indicated the high class of tectonic activity for the study area. Furthermore, the obtained result of tectonic activity was confirmed by fieldwork and previous literature. In this regard, the active tectonics of the study area has corresponded to the highest values of sediment yield, soil losses, dynamic failures, and various types of landslide events.

Keywords Geomorphic indices · Active tectonics · Drainage basin · Iran

1 Introduction

Geomorphic indices play an imperative role in understanding the essence of movements, as well as interpreting the regions' tectonic status. Due to the lack of seismotectonic data in different parts of the world, it is necessary to investigate the tectonic activity by intermediate quantitative assessment of geomorphic indices and characteristics. The results of a quantitative assessment of geomorphic indices can be combined to highlight tectonic activity and to provide an assessment of a relative degree of tectonic activity in an area [1, 2]. Quantitative assessments make it possible for geosciences researchers to evaluate different landforms using measurable indices [3].

Geomorphologic indices providing a wide range of characteristics have been used in different regions such as southeast mountains of Spain [4], Sierra Nevada mountain range of Spain [5], Hindu Kush mountains of northern Pakistan [6], and southwest coast of India [7]. Many researchers have concerned the methodology of active tectonics assessment in Iran, e.g., [8–11]. The most papers have focused on Zagros mountainous zone, and a few types of researches are observed for other tectonically active regions of Iran. Tectonic activity in Iran could be characterized by elevation, recent volcanism, and many active faults [12]. As mentioned by [13], in mountainous basins, active tectonics can be observed contributing to up–down elevated topography resulted from tectonic and erosive processes. Hence, all mountainous basins in Iran are prone zones to active tectonics.

The present study aims to assess the relative active tectonics of a mountainous in the Binaloud mountainous zone, northeastern Iran. For this purpose, some geomorphic indices in the study area called Band-Golestan basin are measured using GIS. The recent papers in

✉ Maliheh Pourali
maliheh.pourali2018@gmail.com

¹ Department of Physical Geography, Ferdowsi University of Mashhad, Mashhad, Iran

² Department of Environment and Natural Resources, Ferdowsi University of Mashhad, Mashhad, Iran

geomorphological analyses have widely attempted to apply of GIS in their researches [7, 14–19].

2 Study area, materials and methods

2.1 Study area

The study area named Band-Golestan basin, including five sub-basins, has a total surface area of about 320 km² and the entire stream length of 30 km. The basin is the main part of the Binaloud mountainous zone between latitudes 36° 08' N to 36° 19' N and longitudes 59° 08' E to 59° 39' E, at northeastern Iran (Fig. 1). Shale and dark gray Phyllite rocks, aged to the Jurassic period has covered the dominant part of the basin (> 73%). The basin includes several faults, formed mainly by contact, fraction, and recrystallization processes between shale and sandstone rocks. The topographical elevations vary from 1080 m above sea level (a.s.l) at the northeast to 3080 a.s.l at the southwest with a mean altitude of 1400 m a.s.l.

Furthermore, the study area is a semi-arid region with a mean annual temperature of 8–10 °C and annual precipitation of 250–300 mm [20]. One of the most essential characteristics of the basin is a dam lake with 18 ha surface area at 1080 m a.s.l, at the outlet of the basin. In the previous articles, this study area has been surveyed only based on geomorphological attitudes. For instance, the result of landslide hazard assessments revealed that principal surface of Band-Golestan basin (above than 55% of total area) has most susceptibility to landslide hazards, which are strongly correlated to the slope angle of the basin including

rock topples, falls and debris landslides [21]. Therefore, the results of erosion and sedimentation model indicated that approximately 60% of the total surface area is classified at massive soil loss and erosion class by calculation the sedimentation and erosion yields above 4000 and 17,000 (m³/km² yr), respectively [22]. In another paper, downstream change in riverbed deposits of the basin has been studied and revealed that the steeper slopes are the main controlling factor of grain size of sediments in the outlet of the basin [23]. Despite the aforementioned geomorphological assessment of the region, there is not any study focusing on tectonic evaluation in the study area. Hence, this paper is the first study on the active tectonic evaluation in the region.

2.2 Conceptual framework

Tectonics studies involve two categories of active tectonics and neo-tectonics, while the application of geomorphic indices is a way to analyze active tectonics. The conceptual framework of this research was designed in a flowchart in Fig. 2. The flowchart assumes that an active tectonics assessment follows the study areas' description and research literature. Then it focuses on a quantitative objective to assess the geomorphic indices. Owing to [24], a modified method for quantitative assessment of active tectonics is assumed and some geomorphologic characteristics are generated including stream length-gradient index (SL), basin asymmetry (Af), hypsometric integral (Hi), a ratio of valley-floor width (Vf), and basin shape (Bs). These indices are supported by both spatial attributions of an extensive fieldwork and data analysis of GIS,

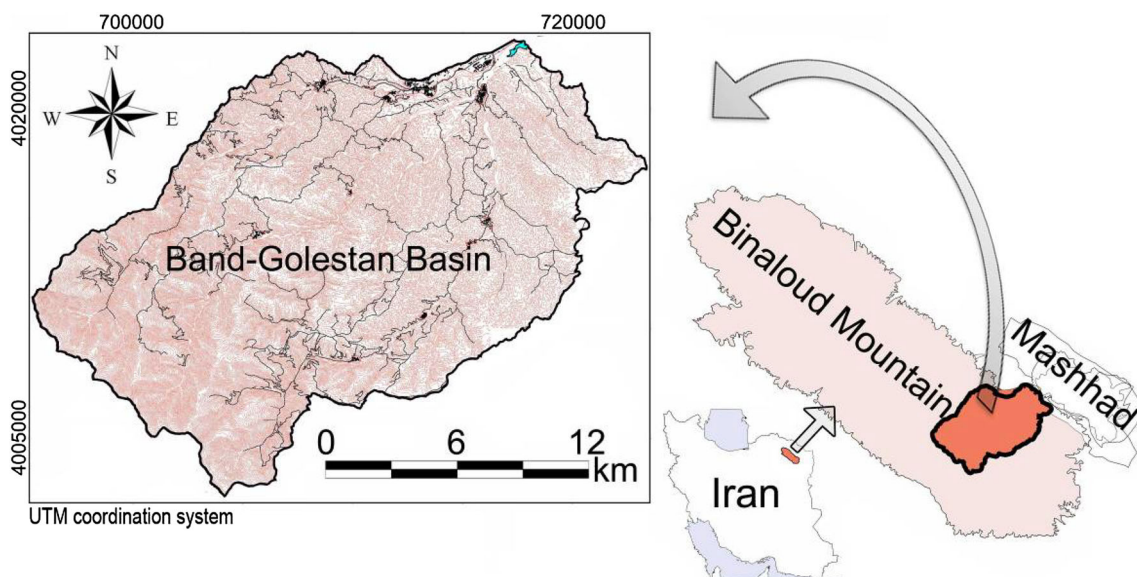


Fig. 1 Geographical position of the study area

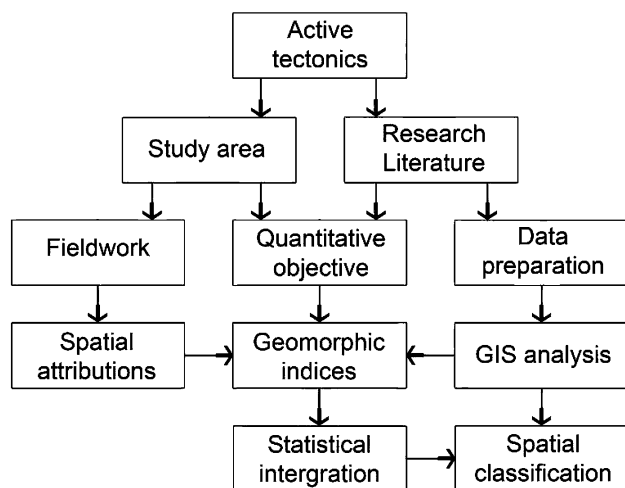


Fig. 2 Flowchart of research methodology

respectively. After the statistical integration of geomorphic indices, an integrated index of relative active tectonics (I_{at}) is estimated. Ultimately, the spatial classification of I_{at} map is produced in GIS, dividing the study area (basin and sub-basins) into four classes from relatively low to very high tectonic activity.

2.3 Data preparation

For preparing data, the principal topographical analysis was derived based on a global digital elevation model (GDEM) via National Aeronautics and Space Administration [25] and was processed into a geographical information system (GIS). Based on DEM, several 3-dimension and spatial analyses of geometric calculations, terrain profile graphs, and geo-statistical models were carried out by GIS for basin boundaries, topographic contours, and drainage streams. Therefore, geological data were extracted from shape maps at the 1:100,000 scale via the Geological Survey of Iran [26]. In this regard, the geological map was gridded from geo-referenced shape-files into raster files with a pixel size of 90×90 m, close to DEM resolution. In the fieldwork, a handheld Trimble GeoXH geographical positioning system (GPS) was used to detect geomorphologic and tectonic features and hazards. In addition to the geological and topographical data and comprehensive field observations, satellite imagery data by Google Earth.

2.4 Geomorphic indices of active tectonics

2.4.1 Stream length-gradient index (SL)

The SL index was defined by [27] to discuss influences of environmental variables on longitudinal stream profiles and

to test stream has reached equilibrium or not. SL is calculated using the follow equation:

$$SL = S_m \times L_m \quad (1)$$

where SL is stream length-gradient index, L_m is the total length of stream from the highest point in the upstream to the midpoint and S_m is the slope of stream along the basin representing the elevation height with respect to length of the basin. The SL index will increase in value as rivers and streams flow over active tectonics [1]. Values of the SL index over the study area, are determined from digital elevation model (DEM) and geographic information system (GIS) indicating three classes of tectonic activity with values of 1: active ($SL > 500$), 2: semi active ($300 < SL < 500$) and 3: inactive ($SL < 300$) conditions.

2.4.2 Basin asymmetry (Af)

Af is a way to evaluate the existence of tectonic tilting at the scale of a basin, which could be applied over a relatively large area [28]. Af is defined by follow equation:

$$Af = (A_r/A_t) \times 100 \quad (2)$$

where Af is drainage asymmetry, A_r is optional area defined as right-hand area of the stream facing to downstream and A_t is the total area of the basin. If the Af value be closed to 50 then the basin has developed under stable conditions with little or without steep slopes. An Af value above or below 50 may result from basin tilting affected by from active tectonics or differential erosion. Its three classes of tectonic activity are categorized as values 1: active ($SL > 75$ or $SL < 25$), 2: semi-active ($25 < SL < 45$ or $55 < SL < 75$), and 3: inactive ($45 < SL < 55$) conditions.

2.4.3 Hypsometric integral (Hi)

Hi is defined as the area below the hypsometric curve and thus expresses the volume of a basin that has not been eroded [29]. The simple equation to calculate Hi defined by follows equation [6]:

$$Hi = \frac{E_{\text{mean}} - E_{\text{min}}}{E_{\text{max}} - E_{\text{min}}} \quad (3)$$

where the elevation values of mean (E_{mean}), maximum (E_{max}), and minimum (E_{min}) in the basin are obtained from a DEM. In general, high values of the hypsometric integral are convex, and these values are generally > 0.5 , indicating class value of 1. Intermediate values tend to be more concave-convex or straight, and generally have values between 0.4 and 0.5, indicating class value of 2. Finally, lower values (< 0.4) tend to have concave shapes, indicating class value of 3 [24].

2.4.4 Ratio of valley-floor width (V_f)

V_f is a geomorphic index conceived to discriminate between V-shaped and U-shaped flat-floored valleys [30]. This index is defined by a modified follow equation:

$$V_f = \frac{2V_{fw}}{V_h} \quad (4)$$

where V_{fw} is the width of the valley floor across the stream and V_h is the valley height based on the difference between the left/right valley divides and the valley floor across the stream. Deep V-shaped valleys ($V_f < 1$) are connected with linear, active down cutting streams distinctive of areas subjected to active uplift, while flat floored (U-shaped) valleys ($V_f > 1$) show an attainment of the base level of erosion mainly in response to relative tectonic quiescence [6]. In this study, values of the V_f index are determined from DEM indicating three classes of tectonic activity with values of 1: active ($V_f < 1$), 2: semi active ($1 < V_f < 2$) and 3: inactive ($V_f > 2$) conditions.

2.4.5 Basin shape (B_s)

The horizontal projection of basin shape may be described by the basin shape ratio (B_s) [31], which is expressed by below equation [9]:

$$B_s = B_l/B_w \quad (5)$$

where B_l is the length of the basin measured from upstream to outlet of the basin, and B_w is the width of the basin measured across widest point. According to El Hamdouni et al. [24], values of the B_s index are categorized as active ($B_s > 4$), semi active ($3 < B_s < 4$) and inactive ($B_s < 3$) conditions for relative tectonics, exposing class values of 1, 2, and 3, respectively.

2.4.6 Index of relative active tectonics (I_{at})

According to [24], I_{at} is obtained by the average class values of geomorphic indices as below equation:

$$I_{at} = S_i/N \quad (6)$$

where S_i is the sum values of all indices comprised of 1, 2, or 3 (depending on the active, semi active and inactive class), and N is the number of indices that is equal to 5 in this present study. Mean values of I_{at} could be divided into four intensity classes revealing very high ($1.0 < I_{at} < 1.5$), high ($1.5 < I_{at} < 2.0$), moderately ($2.0 < I_{at} < 2.5$) and relatively low ($I_{at} > 2.5$) activity of tectonics.

3 Results and discussion

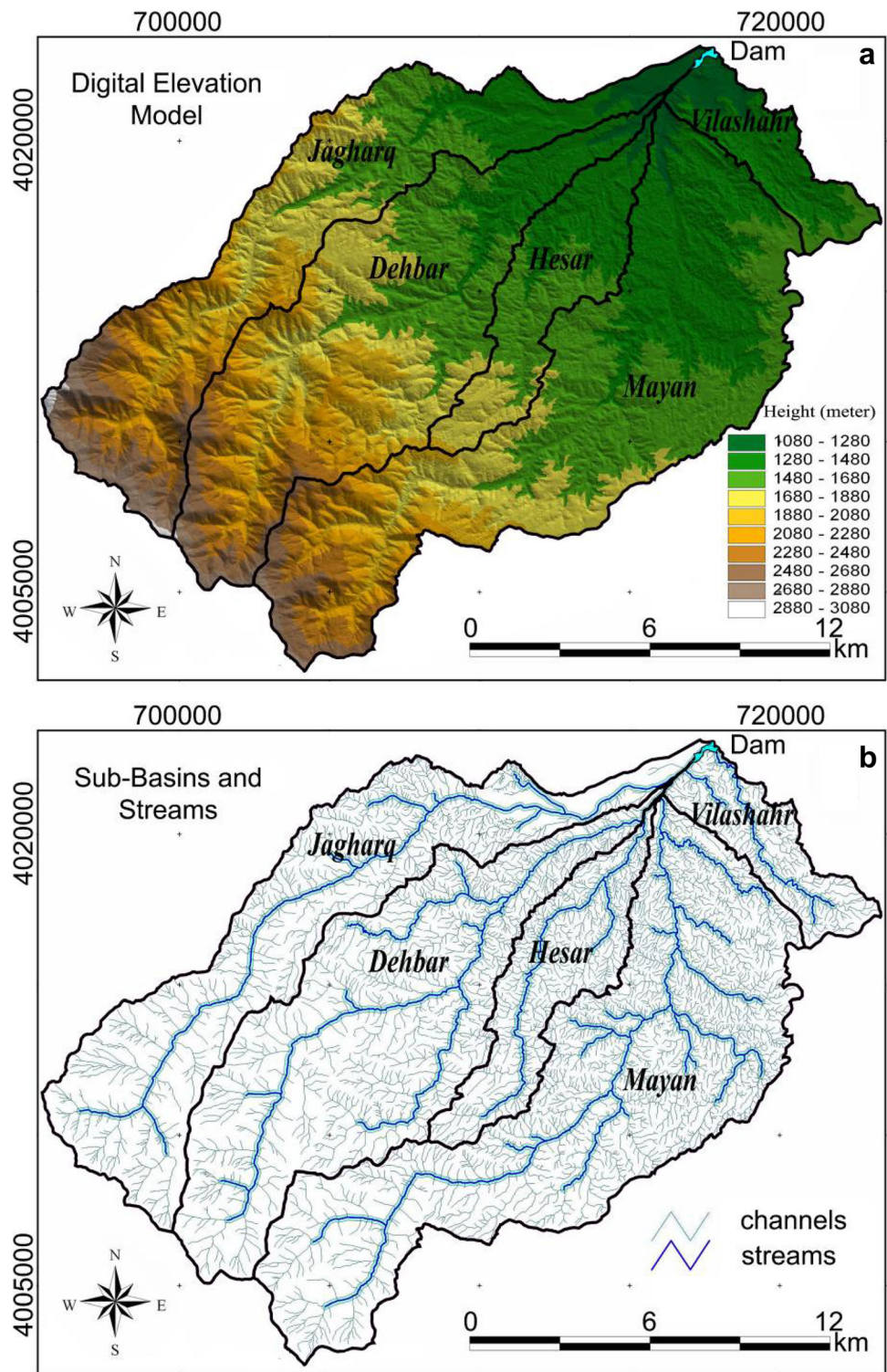
3.1 Interpretation of controlling data and fieldwork

DEM provides an opportunity to quantify land surface geometry in terms of elevation heights, slopes, and aspects. DEM is an excellent source to derive topographic attributes responsible for geomorphic activity in a region. The elevation data in the basin consist of several height classes from 1080 m as the lowest point to 3080 m as the highest point (Fig. 3a). Besides, the possibility of extracting stream network with stream gradients and sub-basin surface areas is one of the most critical processes on DEM. Rivers and streams data layer can be prepared by digitizing the drainages from the topographic maps (Fig. 3b). This map indicates detailed characteristics of watershed analysis based on sub-basin boundaries, main streams, and drainage channels. On this basis, the primary drainage trend in the southern part of the basin is SW–NE with a dendritic pattern, while this trend affecting by South Mashhad (SM) and Sangbast-Shandiz (SS) faults alter locally to NW–SE with a rectangular pattern in the northern part of the basin. This variation also relates to geological units and outcrops.

The geology of the study area is divided into shale/phyllitic, ultrabasic, sandstone, and quaternary terraces (Fig. 4a). The dominant geological formation of shale/phyllitic is a low-grade metamorphic rock derived from fine-grained sediments and contains a large amount of aligned mica, which imparts a coarse splitting plane. Landslides are affected by stress release along micro faults, which have been mainly observed along with linear failures. Based on the fieldwork observations, it seems that the study area has many pieces of evidence of ancient and neo-tectonic activities such as the joints, folds, fractures, faults, landslides, and erosional features. Depending on the shale and phyllitic rocks in the study area, various recent deformations and outcrops were observed in the basin, which results in various types of landslide hazards such as debris slides.

To complete the inventory of landslides, in addition to field data, depository data of recent official studies, e.g., [21, 22], were considered to record all the susceptible prone zones of landslides in Fig. 4b. On this basis, more than 70% of the landslide occurrences corresponded to geographical prone of lithologic contacts, micro-fractures, and faults in the southern and northern basin, respectively (Fig. 5). Several faults and fractures have influenced to change the landscape patterns and landslide occurrences. The dominant trend of the corresponding fractures was observed in the NW–SE direction perpendicularly on the dominant physiographic trend of the basin.

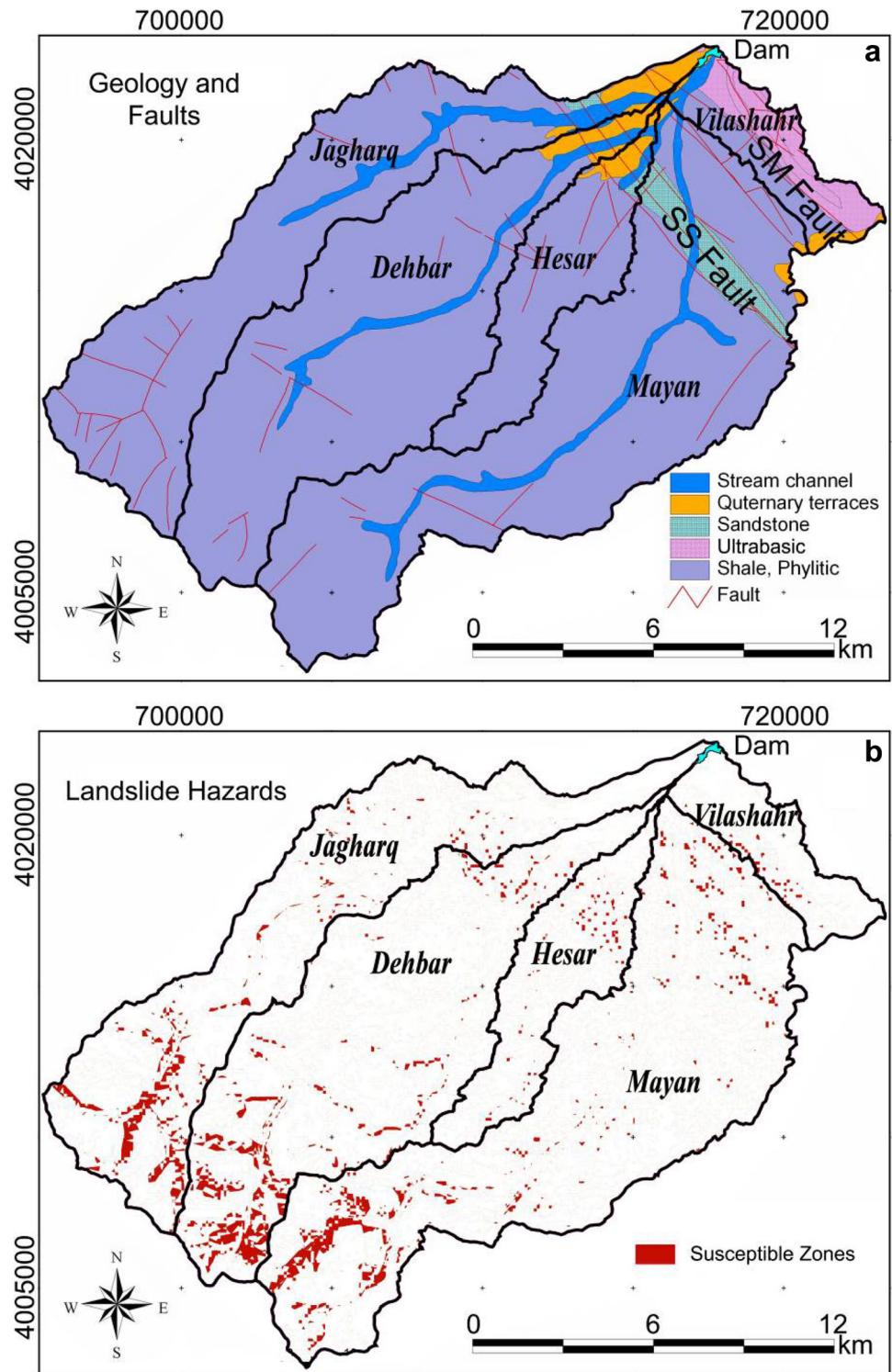
Fig. 3 Topographic database layers in the study area.
a Digital elevation model.
b Detailed characteristic of sub-basins and streams



The main fault features of the study area are called as South Mashhad (SM) fault and Sangbast-Shandiz (SS) fault comprising parallel thrust-right lateral slip faults with the strike of NW–SE at a width of 3 km and length of about 100 km [32], which are commonly assigned as the northern border of the region at basin outlet. Therefore, the

existence of intersecting micro faults across the central valleys of the sub-basins indicated a new stress mechanism, which can trigger mass movement events. In brief, the basin tectonics corresponds to Binaloud tectonics, which is an eastern segment of the Alborz Mountains, affecting by thin-skinned tectonics [33].

Fig. 4 Geo-database layers in the study area. **a** Distribution of fault lineaments, geological units. **b** Landslide susceptible zones based on Bagherzadeh and Mansouri Daneshvar [21]

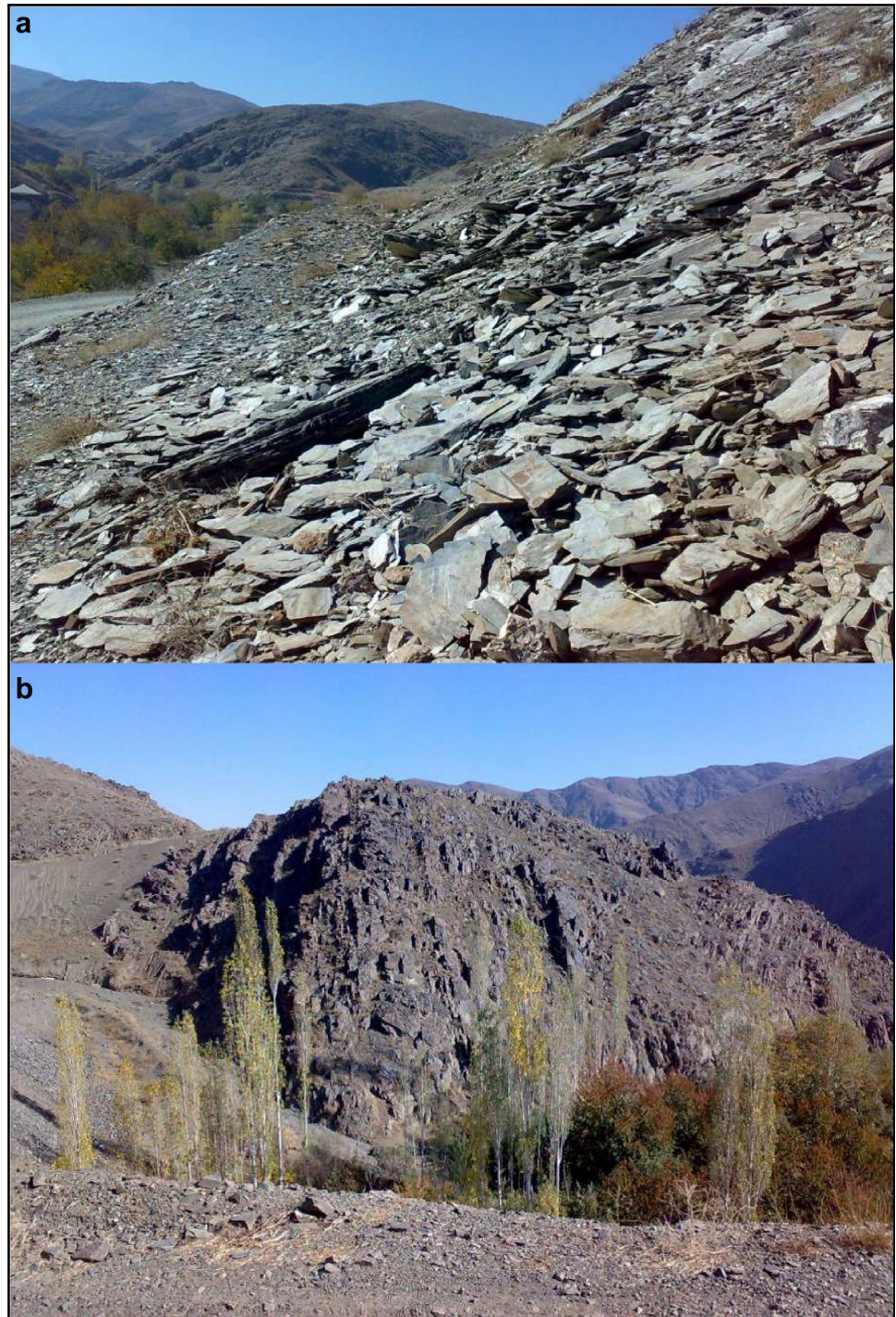


3.2 Geomorphic indices to assess active tectonics

Geomorphic and geometric indices have been considered as essential tools by many researchers to determine tectonic activities in the active areas using GIS that automatically calculate the indices. Based on the methodology, the first

geomorphic index to assess active tectonics is the SL. SL is depended on the variations of the river's slope relating to stable or unstable activities of tectonic. The best technique is using the length profile of the main central stream. In all sub-basins, the SL values were calculated along with the profile graphs of the main streams. Averagely, SL values

Fig. 5 Natural landscape of the study area. **a** Landslide event over shale and phyllitic debris in the southern basin. **b** Vertical feature of micro fault fraction on the sandstone rock in northern basin



were estimated from 150 to 800 (Table 1). Among the study area, Jagharq, Dehbar, and Mayan sub-basins indicated values of SL index higher than 500 exposing the active tectonics. Accordingly, above 85% of the basin is under an active class of tectonic activity. Figure 6a shows a profile graph for Dehbar River, indicating its mean slope gradient of 6% along with upstream to downstream.

The second index, named drainage Af, can help to identify the tilting and asymmetry of the basin's tectonic. If the Af value is close to 50, it can be claimed that the basin is affected by the tectonic forces with an asymmetric shape. However, the Af values greater or lesser than 50 indicate the tilting streams to the right or left sides of the basin. In this study, the Af values were estimated between 37.50 and 61.61 (Table 1). Among the study area, the Af index was

Table 1 Detailed characteristics of geomorphic characteristics and indices in the study area

Geomorphic characteristics	Symbol	Sub-basins of Band-Golestan				
		Jagharq	Dehbar	Hesar	Mayan	Vilashahr
Total area (km ²)	At	75	90	27	112	16
Perimeter (km)	Pt	69	60	37	71	24
Basin length (km)	Bl	25	22	13	20	8
Basin width (km)	Bw	5	7	3	6	2
Basin shape (-)	Bs	5.00	3.14	4.33	3.33	4.00
Height of basin (m)	Ht	2000	1900	700	1600	300
Slope of basin (%)	St	0.08	0.09	0.05	0.08	0.04
Length of stream (km)	Lm	27	28	10	25	5
Height of stream (m)	Hm	1600	1600	500	1400	300
Slope of stream (-)	Sm	0.06	0.06	0.05	0.06	0.06
Stream length-gradient (-)	SL	800.00	800.00	250.00	700.00	150.00
Optional area (km ²)	Ar	30	45	12	69	6
Drainage asymmetry (-)	Af	40.00	50.00	44.44	61.61	37.50
Min elevation (m)	Emin	1100	1100	1200	1200	1200
Max elevation (m)	E _{max}	3100	3000	1900	2800	1500
Mean elevation (m)	E _{mean}	1800	1700	1400	1500	1300
Hypsometric integral (-)	Hi	0.35	0.32	0.29	0.19	0.33
Valley height of stream (m)	Vh	55	50	15	30	10
Valley floor width (m)	V _{fw}	70	70	40	80	30
Valley floor ratio (-)	Vf	1.27	1.40	2.67	2.67	3.00

estimated equal to 50, exposing the active tectonics and asymmetric shape.

Fore third index, Hi, is used to express the dispersion of the highlands in the breadth of a basin. The hypsometric curve of a basin presents the distribution of area and altitudes within a basin. The relative area below the curve expresses the volume of erosion activity [8]. Figure 6b shows that the basin's hypsometric curve is in a developing and logging stage. Likewise, the convexity of the hypsometric curve indicates the tectonic activity of the basin affected by erosion processes. In this study, the Hi values were estimated between 0.19 and 0.35 (Table 1). The Hi-index values were estimated averagely below 0.4 for all sub-basins exposing the active tectonics and concave shape of the hypsometric curve.

In the fourth step and to calculate a ratio of Vf along the basin's main river, five valleys were identified and selected. Accordingly, by plotting the width profile of the valleys, the values of the maximum height of the two sides of the valleys, the height of the valley floors, and the width of the valleys were measured (Table 1). In this study, the Vf values were estimated between 1.27 and 3. Among the study area, Jagharq, Dehbar, and Mayan sub-basins indicated values of the Vf index below than 2 exposing the active or semi-active tectonics.

In the fifth step, the index of Bs is estimated. In tectonically active areas, basins have elongated shapes. The

elongated shape is transformed into circular basins as tectonic activity diminishes with time and continued topographic evolution [30]. In this study, the Bs values were estimated between 3.14 and 5 (Table 1). The Bs index values were estimated averagely above 3 for all sub-basins exposing the active or semi-active tectonics and elongate shape of the sub-basins.

In the final step, Iat was calculated as the average of geomorphic indices. The average of the five aforementioned measured geomorphic indices was used to categorize the classes of relative tectonic activity in the study area (Table 2). The obtained results from the calculation of the active tectonics index revealed the Iat values between 1.4 and 2.4 and a mean value of 1.88 for the whole Band-Golestan basin indicating a high class of active tectonics. Among the study area, Jagharq, Dehbar, and Mayan sub-basins indicated values of Iat below than 1.5 exposing the very high class of active tectonics (Fig. 7).

According to [22], the highest values of mean sediment yield and mean soil loss corresponded to these sub-basins. It can be expected that in all high and very high classes of active tectonics, the sedimentation and erosion processes can be categorized in highest values due to slope instability, dynamic failures, landslide events, and other geomorphic alterations. Based on the DEM analysis, more than 50% of total surface areas in these sub-basins covered by steeply slopes (> 15%). Hence, the results of the classes of

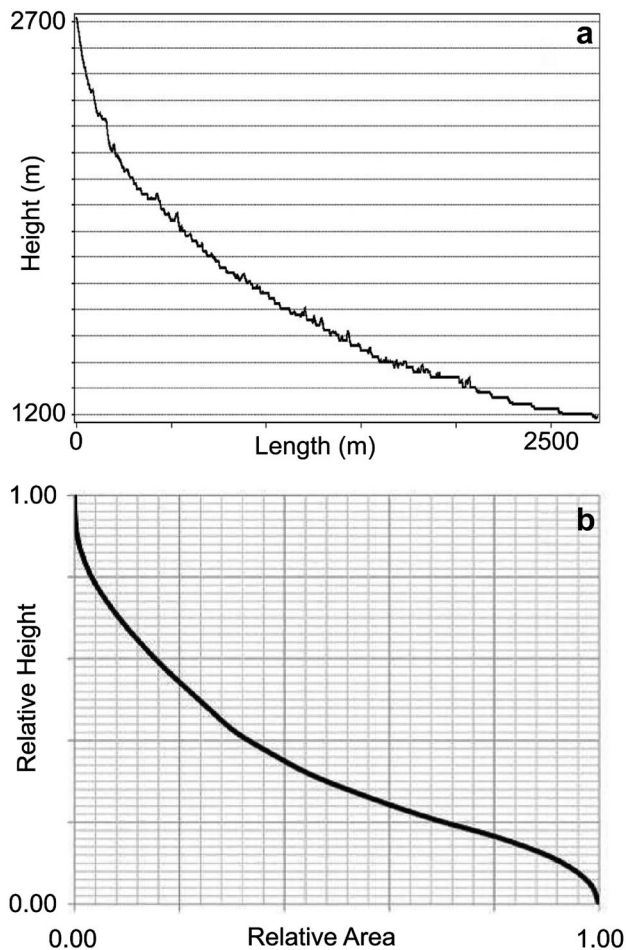


Fig. 6 Data plots of the basin. **a** Profile graph of the main stream of the basin along the Dehbar River. **b** Hypsometric curve of Band-Golestan basin

relative active tectonics are adapted to actual status in the region. The active tectonics of the study area can be confirmed by the right lateral displacement, separation from the mountain front, and gradual displacement from west to east of exodus alluvial fans of the Band-Golestan basin,

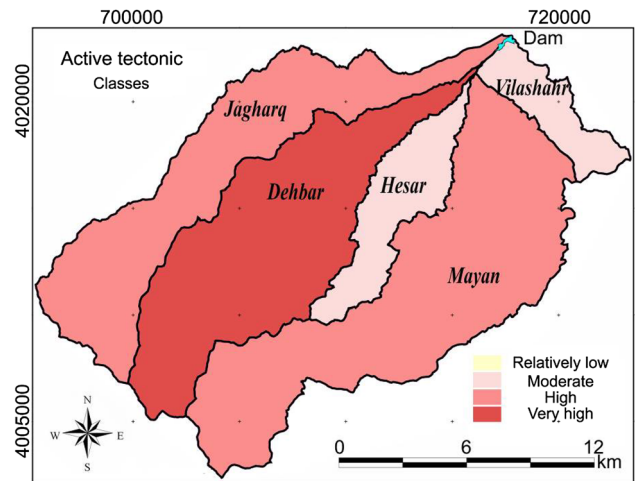


Fig. 7 Classes of relative active tectonics in the study area

which has been surveyed as a part of Binaloud old and new alluvial fans by [34].

4 Conclusion

This research aimed to investigate the tectonic activities in the Band-Golestan basin, which is located in northeastern Iran. For this purpose, five geomorphic indices were considered to study the relative active tectonics, including SL, Af, Hi, Vf, and index of Bs. By averaging the indices, Iat was obtained. According to the results of the mean values of five indices, the whole basin has active or semi-active tectonics. The overall index of Iat with a value of 1.88 indicated the high class of tectonic activity for the study area. Among the study area, Jagharq, Dehbar, and Mayan sub-basins indicated values of Iat below than 1.5 exposing the very high class of active tectonics.

In the study area, especially in the southern basin, tectonic activity has made the vertical nature of the faces outcrops with recent changes in quaternary. In the northern

Table 2 Class values of indices and active tectonic index in the study area

Geomorphic characteristics	Symbol	Sub-basins of Band-Golestan				
		Jagharq	Dehbar	Hesar	Mayan	Vilashahr
Basin shape	Bs	1	2	1	2	2
Stream length-gradient	SL	1	1	3	1	3
Drainage asymmetry	Af	3	1	3	2	3
Hypsometric integral	Hi	1	1	1	1	1
Valley floor ratio	Vf	2	2	3	3	3
Active tectonic index	Iat	1.6	1.4	2.2	1.8	2.4
Active tectonic class	–	High	Very high	Moderate	High	Moderate

basin and over the ultrabasic formation, the activity is observed with ancient evidence aged pre-Quaternary. Therefore, the results of the classes of relative active tectonics are adapted to actual status in the region. The active tectonics of the study area corresponds to the highest values of sediment yield, soil losses, dynamic failures, and landslide events through the sub-basins. So, it can be confirmed by the right lateral displacement, separation from the mountain front, and gradual displacement of exodus alluvial fans of the basin.

This study suggests that the active tectonics prone zones must be protected toward the rising physical sprawl of urban and suburb developments in the study area. Contrarily, these zones could be considered as pilot stations for future studies of active tectonics, supporting the mitigation measures of environmental hazards, earthquake prediction, etc. The proposed method of this study, instead of limitation, has the potential to supply more geomorphic indices. Due to the integration method of Iat, the method could be extended by using enormous indices. In this regard, GIS-based characteristics of sedimentation and erosion models, in addition to seismic induced changes of the lithosphere, are proposed for further studies.

Acknowledgements We thank anonymous reviewers for technical suggestions on data interpretations.

Authors' contributions All authors were equally involved in analyzing and editing the paper.

Funding This study was not funded by any grant.

Availability of data and material The data that support the findings of this study are available from the corresponding author upon request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval and consent to participate This article does not contain any studies with participants performed by any of the authors.

Informed consent Informed consent was obtained from individual participant included in the study.

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