Chapter 4

Tectonic Geomorphology

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4-1-General Statement


The development of folds in Zagros Structural Belt are from north east to south west at the rate of 30 mm/yr (Berberian 1995), with a maximum fold crest uplift rate of 1cm/yr. Once fold growth has ceased, the landscape remains subject to uniform uplift at rate of 1mm/yr due to crustal thickening at depth. Uplifting and folding are the two main factors that form a series of parallel streams in lowlands between the rising folds. As the uplift is continuing, the drainage networks are adjusting and controlling the structure and lithology. The drainage network can be used as an important tool to interpret the structural behaviour of the area.

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The river profile drainage network is mainly used for estimation of tectonic interpretation in the study area. The structures are controlled by the kinematics regimes. The drainages and geomorphic features are also controlled by structures such as faults, folds, joints and lineaments. Rivers, which have seen in the Zagros Structural belt are Dez, Kashkan and Karkheh. Some of these rivers after flowing a long distance finally ended in Persian Gulf. Morphotectonic evaluation of the Dez river (Fig. 4-1) is selected due to its importance. The Dez river was digitally drawn from contact of Sanandaj-Sirjan Zone and high Zagros (Imbricate Zone) where Main Zagros Thrust is located (Fig. 4-1). This river is originated at Chalanchoolan police station, which is 25 km southeast of Brojerd city. The Dez river crosses the Dezful city at south west of the study area in Dezful embayment.

![Fig.4-1) Showing Dez river on DEM of the study area](image)

Thrusting is implicated in the tectonic evolution of the belt. Propagation of faults through basement blocks and palaeo-basins controls the geometry of these structures (Inger et al. 2002).
In this study emphasis has been given mainly on cross-section of the topographic profiles for estimation of net erosion rates, river profiles, stream-gradient indices, generation of different geomorphic maps and assessment for querying of sinuosity, SL-slope, drainage density in the GIS environment to evaluate the tectonics of the study area.

4-1-1-Methodology

Materials used are: 1) Digital Topography Maps in DGN formats 2) Landsat-5 No.166-037 TM and ETM with different FCC, dated June 1991 and November 2002 respectively 3) various softwares like Rivertools 2.4, Microstation, ENVI 3.5, ER-Mapper 6.1 4) Arcview 3.2 5) geological map of Iran.

The Digital Topography Maps in DGN format from ISO have been converted in text format with the help of Microstation software and finally introduced in Rivertool software to prepare DEM.

The satellite data were used in field visits to identify the objects in the study area. The ER-Mapper 6.1 and ENVI 3.5 softwares were used for georeferencing and Digital Image Processing. Geological map and DEM of the study area were calibrated, to characterize the relative age and formation of each rock unit for calculation of the net erosion rate. A profile of the Dez river was digitally mapped using Rivertool software to deduce the stream gradient for tectonic interpretation of the study area.

Three topographic profiles were drawn separately on DEM, which are approximately perpendicular to NW-SE (trend of main Zagros Structural Belt) to calculate the net erosion rates. The strategy for calculating the net erosion rates using DEM was

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normally to subtract the present topography from the filled topography, which yields a volume of eroded material. The actual total mass loss was approximated by connecting the higher points (dashed line) but this is a more subjective interpretation (Burbank and Anderson, 2001). Emphasis was given to the initial landform shape, topography and the initiation of folding to calculate net erosion rates. After creating a reference surface in the topographic profiles (Fig. 4-16 4-17, 4-18) that connect all of these erosional remnants and then subtracting the modern topography from this surface, the average amount of erosion, as well as local erosion estimates at each point, have been made (Small and Anderson, 1998). Further more GIS software was used to generate sinuosity map and SL-Slope map which direct us for a good tectonic interpretation of mountain front.

4-2- Tectonic and Landscape Evolution

“Tectonic landforms” are structural landforms of regional extent. These landforms are making up extensive landscape whose topography is strongly influenced by the structures and some degrees of deformation. Basically landscape developed on orogenic belts in uplifted area and basins in the Zagros Structural Belt can be named as tectonic landforms.

In the study area, fractures and other structural features generally control the geomorphology, which is also strongly influenced by erosion. So the term of “Structural geomorphology” is also used in this text.
Tectonic deformation and interaction with surface process over interval of thousands of year in the Zagros Structural Belt produced the landscapes that we see today in study area which supposed to be tectonically active region. A vertical uplift in the Zagros Structural Belt, hundreds of meters of uplift occur over intermediate geological timescale.

The geomorphological study of the Zagros collision zones reveals that the Zagros morphogeny is the morphotectonic expression of the Alpine-Himalayan subduction cycle and collision between Iranian and Arabian plates. During the Cretaceous the subduction started as a global event which led to the closing of the Neo-Tethys (Takin 1971, Berberian and King 1981) in Iran. This event is recorded as Imbricate Zone where the subduction is related to ophiolite and coloured melange were accreted to the Zagros sediments in the late Cretaceous time (Takin 1972). Collision related compressional tectonics resulted in the upliftment of the Imbricate Zone and the formation of the Zagros Fold Belt and sedimentary environment change from marine to continental in the Zagros trough. The Zagros trough closed around Miocene (25-5 Ma) concomitantly with the opening of the Red sea. The collision of the Arabian and Iranian plates led to the annihilation of the subduction below the Imbricate Zone. This process of collision generated morphogeny in the Sanandaj-Sirjan Zone, Imbricate Zone and Zagros Fold Belt. In response to opening of the Red sea the Sanandaj-Sirjan Zone and Imbricate Zone underwent vertical tectonic and acted as areas of positive relief.

The geomorphological study of the Zagros Structural Belt shows the evidence of morphotectonic activities. The presence of structural features in the Zagros Structural Belt are affected by the pattern of drainages and the main river such as Dez river (Fig.

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4-1). The geomorphic erosion and tectonic denudation (i.e. process of extension and normal fault) (Burbank and Anderson, 2001) with faulting and folding formed V-shape valley in most of the study area.

Structure, processes and time are three pillars of geomorphology. Structure is generally agreed to be the most important of the geomorphological studies in the Zagros Structural Belt. Structures in the Zagros Structural Belt include not only deformation features like folds, faults, and joints, but any characteristics of the rock bodies such as their mineralogy and fabric that govern the relative resistance to erosion.

One of the most profound realization in the study area often looking at the earth from space, where vast area are seen on a single rectified image (LANDSAT-5 TM) (Fig 4-2), is that, over much of the land surface, the major control of the landscape is its underlying structure.

![Fig.4-2) Rectified Landsat-5 TM-1991 image of bands 7-4-1, ZSB SW Iran](image)

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The synoptic views of the geomorphic parameters studied in the area offer strong support that geomorphology, structure and tectonic are related to each other.

The present study shows that the Mesozoic carbonates are exposed in the core of the oldest fold, while erosion has smoothly stripped the younger fold of its Miocene cover in Gachsaran formation. Stream erosion has also stripped off the Miocene marls and evaporates within most of the valleys in the Zagros Structural Belt, exposing the underlying resistant Asmari limestone. With further uplift and exhumation, the drainage network continues to adjust the changing outcrop pattern. The Asmari limestone unit has been stripped off the landscape, with isolated remnants forming synclinal hills.

The pattern of river adjacent to folds and the presence of water gaps (Fig 4-2) in study area can be interpreted to indicate the direction of propagation of folds (Jackson et al. 1996). The main crest of synclinal fold of Asmari formation is impacted by erosional process.

The widely spaced folding in the Zagros Structural Belt represents the propagation and dynamic movement of folds. Overturned and open folding in Miocene age of Gachsaran formation illustrated the tectonic evaluation of Zagros Structural Belt. The Chenareh and Kabirkooh anticlinal folds (Fig 4-3) are the easily visible folds, which are the main asymmetrical folds in the southern part of the study area. Both of these are covered by Asmari formation of Oligocene-Miocene age.
Because of the large fold amplitude the resistant Asmari limestone is chemically weathered along the anticlinal crests, exposing the underlying strata as eroded surface. This topography characterized by resistant hogbacks rimming the inner anticlinal cores and the surface is dominated by the erodible flysch unit (Fig. 4-2).

![Diagram of Landsat image FCC 4 3 2, Dezful block, ZSB SW of Iran](image)

Fig. 4-3) 3-D of the Landsat image FCC 4 3 2, Dezful block, ZSB SW of Iran

The Zagros Structural Belt in south west, Iran is a young ~ 5 m.y (Berberian & King, 1981) and presently an active fold and thrust belt. The combination of field visits and remotely sensed data in the study area shows that the folds have grown up sequentially. Erosion has relatively unroofed many structures in a uniform fashion. Subsequently in the Zagros Structural Belt the geomorphic process acted and degraded the topography of the area. The earthquake is also one of the factors for changing the morphology of the area in the Zagros Mountains.

The low relief surfaces have been less affected by tectonic activities, whereas the Zagros Fold Belt, which has high relief surface and intense tectonic expression, reveals that the Zagros Fold Belt is highly affected by tectonic activities. However,
the main tectonic features that may have direct control over morphotectonic evolution of the study area are described as follows:

4-2-1-Thrust Fault

Thrust faults are reverse faults where the angle between the fault plane and the horizontal is less than 15 degrees. Thrust faults allow large slabs of crust to be stacked on top of another. In the Zagros Structural Belt there are major thrust systems which include the Main Zagros Thrust, Khoramabad Thrust, Jaffarabad Thrust, Hoor river Thrust and Razan Thrust. These are formed due to maximum compressive stress ($\sigma_1$), which is horizontal and is vertically oriented deviatoric tensile stress in the area. These thrusts approximately cut a horizontal land surface at low angle therefore the faults occasionally have been overturned at the surface. Due to the low angle intersection of thrust faults with the earth’s surface, the traces of thrusts are often affected by topography and are highly sinuous.

The Main Zagros Thrust is separating the Sanandaj-Sirjan Zone from Imbricate Zone. The Razan and Khoramabad Thrusts are southwestern extension of the Main Zagros Thrust which are separating different units. The Hoor thrust is just an Imbricate Thrust, which has been generated because of piling up in the Khoramabad klippen and many smaller thrust faults. These faults have accommodated 100 of kms of horizontal movement and have significantly thickened the continental crust in the study area. This thickening of the Main Zagros Thrust (upto 65 Km) of the crust has resulted in the uplift. The directional correlation in the orientation of the major thrust and fold...
axes in NW-SE suggest that the thrusting and folding are dynamically related to crustal shortening in the Zagros Structural Belt.

4-2-1-1- Features of Thrust Faults

**Nappe** - a large symmetrical and asymmetrical fold present in the Zagros Structural Belt indicate the compressional forces and tectonic processes.

**Klippe** - an erosional remnant of thrust sheet is isolated from the main Zagros thrust sheet by erosion.

**Fenster** - (or window) - An eroded valley into a thrust sheet exposes the rocks underlying the thrust fault.

**Scarp** - an immature and rugged topography produced a landscape in the present study area due to thrust faulting.

4-2-2-Strike-Slip Fault

This type of faults are dominated by horizontal movement. This suggests that the principal stress axis is horizontal and direction of the easiest is also horizontal (Badgley 1965). These are seen in the study area like Shahbazan strike slip fault in Zagros Folded Belt. Most of the strike slip faults are causing lateral shift in the lithologies, folds and thrusts.
4-2-3-Fold and Thrust Belts

In the present study zone of the orogen, rocks have been folded into complex anticlines and synclines such as Chenareh and Kabirkooh anticlines (Fig. 4-1). Reverse and thrust faulting occurs along fold axes in the Zagros Mountains (young, active and resistant). Folds and thrust belts in the Zagros Mountains axes are approximately perpendicular to the main compressive stress. Generally folds in the study area have a steeper forelimb than backlimb. The dip of the forelimb is about 60 degrees and the backlimb is about 35 degrees. At places, the uplifted surfaces are seen, which have dissected both forelimb and backlimb of the folds along the fold trend, which may be suggestive of modern geomorphic activities. As the plunging fold began to grow laterally the shorter and steeper stream occur on forelimb and courses the drainage divide to be displaced laterally. Hence across the fold the length of stream develop in asymmetrical fashion. In the study area, the Dez river (Fig. 4-1) can be seen to have cross cutting relationship with folds.

Initially this river tends to maintain its course across a fold. Due to sufficient stream power the uplifted materials are eroded, removed and carried down to stream gradient across the fold axis. The process of erosion has created water gaps (Fig. 4-2) across the fold axis.

As uplift and folding is concerned, in the lowlands and within rising folds a series of parallel streams are formed. The continuation of uplift results the drainage networks related to the structures and lithologies by forming trellis and dendritic to sub...
dendritic drainage patterns. Stream erosion has also stripped off the Miocene marls and evaporates within most of the valleys, exposing the underlying resistant Asmari limestone. Growing uplift results the continuation of drainage networks to adjust the drainage outcrop pattern. The Asmari limestone partially has been stripped off the landscape, with isolated remnants forming synclinal hills.

4-2-3-1- Features of Fold and Thrust Belts

Anticlinal mountains - In Zagros Mountains as folds are exhumed, variation in the resistance of these strata produce topography characterized by large anticline where elliptical Asmari hogbacks encircling breached anticlines, and where exhumation has been greatest, by rugged topography sculpted from Mesozoic carbonates in the inner cores of the anticlines (Oberlander 1965).

Synclinal ridge - Synclinal folding tends to close fractures and thick rock units along the axes of synclines, it is common for synclines to become rugged in the Zagros Structural Belt as the topography of a fold and thrust belt is eroded down. The example of this feature is seen in the Shahbazan area (Fig. 4-1).

Structurally controlled rivers - In Zagros Structural Belt rivers are generally controlled by the structure. Rivers and drainages flow along the axes of synclines, faults and fractures. As the stream system evolves by headward migration and stream capture, the stream may eventually flow across the regional structure in the Zagros Structural Belt (Fig. 4-1).
These structures exhibit tight fold with NW-SE trend and closely space fracture systems. These styles of geological setting facilitated severe erosion and formation of rugged and immature topography with closed drainage system. The drainages also are controlled by fractures and faults system towards NE-SW direction.

**Hogbacks** - The large folds with long amplitude have been caused due to the resistance of Asmari limestone, thereby it is penetrated along the anticline crests, exposing the underlying strata to erosion resulting in the development of hogback features (Fig. 4-4). The hogback ridges in the study area may be characterized by high...
resistance to erosion, structural discordance with the tectonic grain of the Zagros Folded Belt. The hogbacks are observed in some parts of the study area. The main hogbacks are located around south east of Chenarah where Kuh-kavil is situated, around Parasak in north west of Kuh-Kavil, and south west of Hoor river thrust.

3-2-4-Fractures

The well developed fracture system is seen in the Zagros Structural Belt. These are having variable direction to main Zagros trend. However, the density of these fractures and their orientation is well described by Rangzan (1993). Strong control of fracturing pattern on drainage network and erosion in the study area is observed. The high densities of the fractures have affected the area and generate hazards such as landslide and rock fall. The best example of such phenomena which is presented by fracture systems are the Shahbazan, Tang-e-5, Mazou and Keshvar areas in conjunction of Andimeshk-Tehran railway station which pass through the Zagros Structural Belt.

4-3-Geomorphic Study

Tectonic force is an impulsive event that occurs at the beginning of the geomorphic cycle. Subsequently geomorphic process attack and degrade the topography. Since tectonic activities in the area were started during Triassic to Late Cretaceous then the oldest geomorphic features formed in the Zagros Structural Belt that resulted in rugged topography. The tectonic activity in Zagros Structural Belt is more than the
rate of erosion therefore erosion may not be only a considerable process to change the topography and uplifting. In order to determine the relationship between tectonic and erosional activity and also to find the present day morphometric behaviour of the study area, the geomorphological parameters such as drainage basin morphometry, sinuosity, straight line slope, stream gradient indices, drainage basin relief and drainage density are carried out (Tables 4-1, 4-2). These are described as follows.

4-3-1-Drainage Morphometric Analysis

Complex geological-geomorphological activities have created an immature and rugged landscape topography, which in turn imposes various natural hazards (landslide, erosion and flash flooding) causing inconveniences to both people and infrastructure. The area exhibits dendritic to subdendritic patterns. Drainage patterns are not only dependent on the structure and lineaments but also follow the topographic features and patterns.

The use of a digital terrain model of Zagros Structural Belt made it possible to calculate a synthetic drainage system in the terrain and drainage network through which the water runs. A gird-based terrain model of the Zagros Structural Belt represents the continuous surface of the terrain. Drainages are in the direction with the lowest elevation. Each cell has eight adjoining cells and eight possible drainage directions (Bernhardsen 1999). The direction of the drainages based on the cell’s elevation value with the values of the adjoining cells. The drainage network in the Zagros Structural Belt could be automatically vectorized. The digital terrain model (Fig 4-1) made for the area has become a useful tool for the study of drainage

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morphometry. Drainages in the study area also often shift the direction of flow due to folding, thrusting, and rock type variations as the orogen is exhumed (Oberlander and Falcon, 1965).

The new study for drainage basin morphometric analysis of Dez river in the Zagros Structural Belt is evaluated by using GIS software to interpret structure and tectonic behavior in the area. Based on the results from GIS analysis, the following tables are illustrated (Fig. 4-5). Using GIS software for the network analysis make the processes easy to assess the relationships between numbers, Strahler order, length, area, slope (channel gradient), relief, sinuosity, SL-slope, magnitude, drainage density and other geomorphological parameters.

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Table 4-1: Showing data summary for the Dez River Basin, ZSB, SW Iran

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BasinRelief(km)</th>
<th>Basin Area (sqkm)</th>
<th>Drainage Density (1/km)</th>
<th>Network Diameter</th>
<th>No. Of Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orders</td>
<td>Number</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>1</td>
<td>36725</td>
<td>0.0000E</td>
<td>0.0000E</td>
<td>2.58750E</td>
<td>7.75194E</td>
</tr>
<tr>
<td>2</td>
<td>7940</td>
<td>0.0000E</td>
<td>1.37300E</td>
<td>6.25000E</td>
<td>4.90468E</td>
</tr>
<tr>
<td>3</td>
<td>1743</td>
<td>1.0000E</td>
<td>6.2600E</td>
<td>2.8000E</td>
<td>1.54761E</td>
</tr>
<tr>
<td>4</td>
<td>382</td>
<td>1.8000E</td>
<td>9.0000E</td>
<td>2.02050E</td>
<td>2.36447E</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>2.51000E</td>
<td>9.23000E</td>
<td>9.23000E</td>
<td>2.62352E</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>5.88000E</td>
<td>2.81800E</td>
<td>2.71898E</td>
<td>3.41797E</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>2.15000E</td>
<td>6.23500E</td>
<td>3.4677E</td>
<td>3.23616E</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>3.74600E</td>
<td>8.10927E</td>
<td>8.10927E</td>
<td>3.08306E</td>
</tr>
</tbody>
</table>

Table 4-2: Stream Ratio Estimates for the ZSB, SW Iran

<table>
<thead>
<tr>
<th>Name</th>
<th>Ratio</th>
<th>Slop</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream Numbers</td>
<td>4.29</td>
<td>0.633</td>
<td>0.9992</td>
</tr>
<tr>
<td>Drainage Area</td>
<td>4.37</td>
<td>0.640</td>
<td>0.9993</td>
</tr>
<tr>
<td>Straight-line length</td>
<td>1.98</td>
<td>0.297</td>
<td>0.9993</td>
</tr>
<tr>
<td>Along-channel length</td>
<td>2.09</td>
<td>0.320</td>
<td>0.9981</td>
</tr>
<tr>
<td>Elevation drop</td>
<td>1.13</td>
<td>0.053</td>
<td>0.5790</td>
</tr>
<tr>
<td>Straight-line slope</td>
<td>1.78</td>
<td>0.250</td>
<td>0.9649</td>
</tr>
<tr>
<td>Along-channel slope</td>
<td>1.87</td>
<td>0.272</td>
<td>0.9702</td>
</tr>
<tr>
<td>Total length</td>
<td>4.32</td>
<td>0.636</td>
<td>0.9992</td>
</tr>
<tr>
<td>Main channel length</td>
<td>2.30</td>
<td>0.361</td>
<td>0.9988</td>
</tr>
<tr>
<td>Relief</td>
<td>1.53</td>
<td>0.186</td>
<td>0.9716</td>
</tr>
<tr>
<td>Network diameters</td>
<td>2.61</td>
<td>0.417</td>
<td>0.9979</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.05</td>
<td>0.022</td>
<td>0.9967</td>
</tr>
<tr>
<td>Drainage density</td>
<td>1.02</td>
<td>0.008</td>
<td>0.9733</td>
</tr>
<tr>
<td>Source density</td>
<td>1.09</td>
<td>-0.036</td>
<td>0.7720</td>
</tr>
<tr>
<td>Links per stream</td>
<td>2.31</td>
<td>0.363</td>
<td>0.9957</td>
</tr>
</tbody>
</table>

*Equal-weight regression, with minimum order = 2 and maximum order = 6*

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4-3-2-Sinuosity

Several numerical measures of the mountain front and its related fluvial system have been used to classify the state of long-term tectonic activity. Because an active front is generally straight, whereas an inactive one becomes increasingly embayed, the sinuosity of the mountain front is a useful indicator of the level of long-term tectonic activity (Bull and McFadden, 1977). The behavior of long profile was calculated to determine the tectonic activity, which is operating within each lithotectonic unit of Zagros Structural Belt. This is calculated following the formula used by (Burbank and Anderson 2001).

\[
S = \frac{L_{mp}}{L_r}
\]

Where, \textit{sinuosity, S, is determined by dividing the length of the mountain-piedmont junction, L_{mp}, by the length of the associated range, L_r. A sinuosity near to one (S=1) indicate the tectonic active zone} (Burbank and Anderson 2001) \textit{while increasing of sinuosity indices in the area shows that the tectonic processes will be decreased} (Ali et al 2003). Therefore it has been observed that Sanandaj-Sirjan Zone in north east of the study area having higher sinuosity indices than the Imbricate Zone and Zagros Fold Belt (Fig. 4-6). The field data calibrated to the computer analysis in GIS software results that the folded Zagros have been subjected to deformation with high tectonic activities as shown in sinuosity index map (Fig. 4-6). So the study area can be divided in different zones of sinuosity behavior as, 1- Sanandaj-Sirjan Zone with high sinuosity, 2- Imbricate Zone with moderate to high sinuosity and 3- Zagros Fold Belt with low sinuosity.

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The high Zagros near to Main Zagros Thrust on sinuosity map is also implied that the central forces may be applied near to it. So the area will also be subjected to deformation due to tectonic processes where the sinuosity is about 1 to 1.109. It reveals that the axes of deformation within the Zagros Structural Belt are migrating towards south west.

**4-3-3-SL-Slope (Straight Line Slope)**

Calibration of the topography map and field data show that the first-order streams have steeper gradients than the second order streams to which they contribute, and second-order streams are steeper than third-order streams, and so on. Here the high value of SL slope indicates more uplift than lower SL slope. The overlaying SL-slope

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drainage network on Landsat FCC image 7-4-1 (Fig 4-1) indicates the zones with low, moderate and high SL-slope. The low SL-slope shows less tectonic active area while the high values of SL-slope represent high tectonic active area. The area with SL-slope of 0.711-4.268 describes the areas, which are more affected by tectonics than the other lithotectonic units in the Zagros Structural Belt.

The descriptive analysis is used for the study area in GIS environment to make statistical analysis and plots which show the statistical relationships between two parameters. The power of GIS lies in its ability to compare sets of attributes—often thought of as the process of overlaying layers—in order to indicate the X-Y relationship. Generally, the scatter plot in GIS is useful tool to show relationships between attributes. The scatter plot (Fig 4-2) shows the relationships between two sets of attributes in study area. The GIS analysis also could be used to generate other plots of the study area, which is used to interpret structural and tectonic of Zagros Structural Belt.

The relationships between the SL-slope and stream orders in the study area indicated that the first order streams covered high range of SL-slope than second order streams and so on (Fig 4-3). The steeper gradients will also suggest the resistance of the bedrock. In this study, it is deduced that the lower SL slope values correlated with high resistance of bedrock. In Sanandaj-Sirjan Zone where the igneous – metamorphic rocks are exhibited, the resistance will be more than other lithotectonic units where mostly covered by sedimentary strata.

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Fig. 4-7) SL-Slope map overlay on Landsat ETM 741 2002, ZSB, SW Iran

Fig. 4-8) X-Y plot of the stream orders with straight slope in the ZSB.

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4.3-4 Stream Gradient Indices

The zone of rapid rock uplift had a steeper gradient, higher relief, and higher gradient indices (Burbank, 2001). In order to calculate the stream gradient the Dez river profile was digitally drawn from Chalanchoolan police station near Brojerd city, which is in contact of Sanandaj-Sirjan Zone, Imbricate Zone and Zagros Fold Belt. The total length of the stream is approximated to 165 km (Fig. 4-9-A, B). The profile was divided into three sectors such as 1- high Zagros (Imbricate Zone), 2- folded Zagros and 3- folded Zagros towards Dezful embayment in south of Shahbazan station (Fig. 4-10-A, B, C).

Step like river profile of the study area is predicted to approach a graded profile, which indicate that area has been tectonically disturbed. Stream gradient indices deduced in each part of the profile, shows variation from 806m to about 142m per kilometer which means that the river profile is experiencing a regarding stages.

Fig. 4-9-A) Dez river and structural features on DEM of the study area

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Fig. 4-9-B) Dez river profile with about 165km

Fig. 4-10-A) Stream-Gradient indices, topography profile High Zagros
The high index shows the steeper gradient and high tectonic activities are mainly with thrusting and faulting like Main Zagros Thrust, Hoor Thrust, Chamsangar fault, Shahbazan strike slip fault and Baraftab fault (Fig. 4-10-A,B,C). The Dez river profile

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indicated that the most active tectonic zone falls in folded Zagros where the stream gradient indices vary from 806m to 165m per kilometer (Fig. 4-9-B). It has been interpreted that the reduction in gradient towards the Dezful embayment may point towards lesser tectonic activities.

The different formations dominating various type of rocks like limestone and evaporates in Gachsaran formation, shale of Aghajari formation, marls of Kashkan formation, Cretaceous calcareous in contact of the Imbricate Zone and Zagros Fold Belt with Sanandaj-Sirjan Zone may also approaching graded profile of Dez river in the study area.

For the disturbed rivers profile the high SL values or stream gradient may indicate high tectonic activities. The systematic stream gradient map (Fig. 4-11) of the Zagros Structural Belt in GIS environment was made to interpret tectonic correlation. From the map (Fig. 4-11), it is resulted that the Sanandaj-Sirjan Zone that exhibits 0 to 0.441 has low tectonic activity. It also reveals that the Zagros Fold Belt that exhibits 0.441 to 4.268, has higher tectonic activity than other lithotectonic units in the Zagros Structural Belt. These activities in the Zagros mountains have generated terraces.

When a river that is flanked by flight of fluvial terraces is also oriented at a high angle to strike-slip fault (Burbank and Anderson 2001), the terraces displayed by the fault is provided an excellent record of progressive offsets. These terraces have been seen in the study area by changing in river course. Because of changes in river course of
the Dez river through time in the Zagros Structural Belt the height of risers between terraces along strike-slip faults is generally guide to correlate terraces. The vertical (dip-slip) displacement along the faults is responsible for river height and variation as well.

Dez river in the Zagros Structural Belt cross an active fold, so fluvial terraces is recorded as progressive displacement. The presence of fault and continuation in tectonic activities, rupture the surface. The growth of the structure itself was tectonically pulsed, such that terraces formed during intervals of reduced deformation rates (Medwedeff et al. 1992). It is expected that the age and height of the terrace generally correlate with the magnitude of displacement. The field checks show that in the Zagros Structural Belt where the folding and faulting are closely spaced, a single terrace is displaced by several faults.

Fig.4-11) Stream-Gradient map of the study area showing tectonic zones in ZSB.

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4-3-5-Drainage Basin Relief

Uplifted areas are strongly correlated with maximum drainage basin relief which have seen in case of the Dez river with high drainage basin relief. The amount of the drainage basin relief for the study area is mapped ( ) and shows that the area can also be divided into three basin relief zones. These are divided as low, moderate and high drainage basin relief. Low drainage basin relief comprises the Sanandaj-Sirjan Zone with about 0 to 0.661, which indicate low uplifted area with lesser tectonic activities. The high drainage basin relief comprises more uplifted area and higher tectonic activities. The drainage basin of the study area has been shown on DEM as a layer, which is made within the GIS environment ( ).

The use of digital terrain model of Zagros Structural Belt also made it possible to calculate the individual areas and watershed in the study area. The drainage basin was calculated on the basis of cells value. Cell with the lowest accumulated value represent the limit for the Dez watershed ( ) in the study area.

This is the vector representation in GIS environment. The spatial analysis measurement represents polygon for Dez drainage basin, which is totally reliable. For this reason the basin outlet was digitally processed on the DEM for about 277478.58 East and 3626126.6 North with respect to UTM coordinate. The spatial queries for the Dez basin ( ) indicates about 8109.68017578 sq.km area. The study could

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also implement to achieve the watershed sub basin boundaries in the Zagros Structural Belt.

Fig. 4-12) Drainage basin relief of the study area

Fig. 4-13) Drainage basin of the study area overlaying on DEM

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4-3-6-Drainage Density

Drainage density is expressed as length of channel per unit area. If the drainage density is low it indicates harder lithology, whereas higher drainage density indicates softer lithology. In case of sedimentary rocks low drainage density indicates arenaceous rocks whereas high drainage density indicates argillaceous rocks. In igneous terrain the soil cover may be either sandy soil or clay soils. The sandy soils will have low drainage density and indicate subsurface lithology as granites or granitic rocks such as diorite, granodiorite. The clay soils will have high drainage density and the subsurface lithology will be interpreted as basic rocks. In case of metamorphic terrain the low drainage density will indicate gneiss and schists whereas high drainage density will indicate slates and phyllites. It has been studied that if the drainage density is higher, the rate of erosion will also be higher (Pirasteh 2000).

It has been identified (Fig. 4-14) that the erosion regions can be described to interpret the tectonic geomorphological settings. The drainage density map shows the following:

1- The average drainage density in Sanandaj-Sirjan Zone is about 3.218
2- The Imbricate Zone develop with average drainage density of 2.619
3- The average drainage density for the Zagros Fold Belt was calculated to be about 3.8005. It shows the trellis drainage pattern
4- The drainage density for the Molasse Cover Sequence is calculated to be about 1.72.

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The descriptive GIS spatial analysis indicated that the first order streams have higher range of drainage density than the second order streams and the second order streams have greater range of drainage density than third order streams and so on (Fig. 4-14).

Fig. 4-14) Drainage density map of the study area made in GIS environment.

4-3-7-Stream Responses to Regional Tilting

The Dez river is one of the main river in the study area which follows the steeper slopes. Rivers that flow directly downwards a newly created slope are consequent...
rivers (Burbank and Anderson 2001). The uplifting in the Zagros Structural Belt is an interesting point to dissect stream responses. The tectonic evolution of the Dez river (Fig 4-1) is along the surface of uplifted folds. Due to tilting of the faulted blocks Dez river has undergone many changes. At places where rivers flowing along the axis of a basin that tilted is tend to be shunted towards the down dip edge of the basin (Cox 1994). The Dez river flows in the direction of tilting, therefore the study shows that Dez river will often has steeper gradients. The uplifting in the Zagros Structural Belt and erosion processes considerably has changed the situation of the rivers that flow across a surface and slope is changing due to ongoing tilting. Hence this tilting caused the shifting of original river courses towards the steepest gradient.

The Zagros Structural Belt has rugged topography. Therefore it is anticipated that the regional tilting would have steeped the courses of Dez river.

4-4-Resistance to Erosion

In rugged topography of the Zagros mountains, different rock types are seen with varying resistance to erosion. In the Sanandaj-Sirjan Zone where igneous and metamorphic rocks show differential erosion has created low land in metamorphic terrain whereas in igneous rocks it has hummocky surfaces. The rest of the Zagros, which comprise sedimentary rocks also exhibit differential resistance to erosion and hence marls and evaporites form in valleys and low areas. In the study area limestone and sandstone exhibit ridges due to their moderate to high resistance to erosion.
4-4-1-Net Erosion Rates

It has long been recognized that during long interval of tectonic quiescence, topography of the Zagros Structural Belt beveled off by erosion processes and low-relief landscape has developed. It has been recognized that the landscape in the Zagros Structural Belt as an active tectonic belt results from interaction among the processes of uplift in Miocene time and surface processes that can lead to local erosion and deposition. The uplift and erosion during Miocene to Recent has resulted in changing the topography where the altitudes of the peaks have increased and at the same time the mean height of the region is also increased, that is due to continuation in tectonic processes in the Zagros Structural Belt where the height increases 1mm/year.

In the present study to calculate the net erosion rates, emphasis has been given to on the initial landform shape, topography and the initiation of folding. No parameter such as sediment flux, shear stress has been taken into account though many people would argue that the sediment flux is a critical variable in controlling erosion rates. The rate of surface erosion may be calculated as follows:

Rate of erosion = \frac{\text{Elevation of bed rock in } T_2 - \text{Elevation of bed rock in } T_1}{\text{Different in Time scale}}

Where, \( T_1 = \text{Old time} \)
\( T_2 = \text{Present time} \)

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The volume of rock erosion during the deformation in different times and under varying conditions has been calculated. The age of the former erosion helped us to evaluate the elevation of the net erosion rates presently acting in the area. The high relief surface in the Zagros Structural Belt gives the tectonic activities ideas with old erosion surface; therefore the oldest erosion processes in the Zagros Structural Belt developed the rugged topography. Not only topographic elevation, but also the age of the strata defines the rate of erosion. Hence the rate of erosion is correlated to mean basin elevation (Pinet and Souriau 1988). Concordant summit of peak elevation gives the result for erosion process and its rate (Barbank and Anderson 2001).

Geomorphic processes were conceived as attacking the uplifting region throughout the period of Zagros mountains building, so that the resulting landscape could be interpreted as product of these activities between deformation and erosion. The crest of the main anticlinal fold of Asmari formation is affected by erosion processes therefore the topography has been changed to form breached anticlinal landform.

To calculate the surface erosion rate, after creating a reference surface in the topography profiles (Fig.4-15-A), that connects all of these erosion remnants and then subtracting the modern topography from this surface, the average amount of erosion, as well as local erosion estimates at each point, was made (Small and Anderson 1998).

Rapid uplift in the Zagros Imbricate Zone and Zagros Fold Belt especially in Miocene-Recent with high net erosion rates generated rugged topography while in Sanandaj-Sirjan Zone lower rates of net erosion with smooth topography (Fig.4-15-
A,B). Net erosion rates are varied within 10m/MY – about 162.5m/MY. The 1mm/y rates of uplift (Berberian 1976) has not been taken into account. To calculate net erosion rates, three cross-sections are digitally drawn on DEM. These are as follows:

Profile A-B:

The profile has 190 km length. It starts from north east of the study area where Sanandaj-Sirjan Zone exhibits and ends to west of Dez dam, which comprises Pliocene conglomerate and Recent materials. This profile cuts the following lithotectonic zones. 1-Sanandaj-Sirjan Zone, 2- Imbricate Zone, 3- Zagros Fold Belt and 4- Molasse Cover Sequence. The Sanandaj-Sirjan Zone dominated by igneous-metamorphic rocks of Jurassic-Triassic age. The other lithotectonic units comprise sedimentary rocks from Recent and Pliocene age to Cretaceous. The topographic profile cuts the Zagros Fold Belt in 50 km to 140 km and shows that the area has been subjected to more deformation with closely spaced folding (Fig 4-15-A, B).

The average net erosion rates in the Zagros Fold Belt estimated about 54.16 m/m.y. The topographic profile also cuts Sanandaj-Sirjan Zone in northeast. The net erosion rates were calculated for this zone. That is about 13.7 m/m.y. The sudden changes can be observed in the topographic profile.

These changes can be interpreted as a major difference in lithotectonic units. About 70 km from southwest to north east, the profile shows sudden decrease in elevation. The surface erosion calculated about 110.52 m/m.y for this region of Molasse Cover.
Sequence. Along the cross-section A-B (Fig. 4-15-A, B), for about 50 km from north east to south west where Main Zagros Thrust is present, there are numerous variation in elevation. This also can be described as a boundary for the divisions of the two lithotectonic units.

However, this profile indicates that the Zagros Fold Belt has high net erosion rates and uplift than the other lithotectonic units. It also shows that the continuous erosion process within the Zagros Fold belt has developed a rugged and immature topography.

Profile C-D:

The profile along cross-section C-D has 110 kms length. It starts from south of Brojerd city where the contact of Sanadaj-Sirjan Zone and High Zagros (i.e. Main Zagros Thrust) is present and ends north west of Andimeshk city in the south of the study area. This profile cuts Imbricate Zone in northeast and Zagros Fold Belt in southwest.

This profile also consists of different lithological units such as Cretaceous calcareous, Asmari Formation, Gachsaran Formation, Papdeh and Gurpi Formations. The profile shows that the net erosion rates in the Zagros Fold Belt for Papdeh and Gurpi Formation is about 64.28 m/my, Gachsaran Formation (Miocene-Eocene) about 52.94 m/my and Asmari Formation about 45.16 m/my.

The net erosion rates average in the Zagros Fold Belt, from the profile is depicted about 162.38 m/my. The profile also shows the average of the net erosion rates calculated in Imbricate Zone is about 21.9815 m/my (Fig. 4-16-A, B).
However, the profile indicates that the uplifting and surface erosion rate in the Zagros fold Belt is more than that of Imbricate Zone.

Fig. 4-15-A) Digital topography of dissected area in ZSB, SW Iran

Comparative Topography profile of SSZ & ZSB to estimate erosion rate

Fig. 4-15-B) A-B Cross-section of NE-SW of ZSB, SW Iran

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Fig. 4-16-A) Digital topography of dissected area in ZSB, SW Iran

Topography profile of Western ZSB to estimate erosion rate

Fig. 4-16-B) C-D cross-section of dissected area in ZSB, SW Iran
Fig. 4-17-A) Digital topography of dissected area in ZSB, SW Iran

Fig. 4-17-B) E-F cross-section of dissected area in ZSB, SW Iran
The profile along cross-section E-F is 87 km in length. It starts around Dorood police station in northeast, contact of Sanandaj-Sirjan Zone and High Zagros of Main Zagros Thrust and ends to north east of Andimeshk city (near Shahbazan station) (Fig 4-17-A. B). This profile cuts two lithotectonic units. These are:
1-Imbricate Zone
2- Zagros Fold belt, in east of the study area.

The area comprises different sedimentary rocks from Cretaceous to Recent and Sub Recent. The net erosion rates calculated for each unit has given in figure Fig 4-17-A. B that varies from 36.58 to 162.5 m/my. The profile shows the rugged topography in the area.

The profile also presents water gaps in the area which was caused due to folding (Fig 4-17-A. B). Interpreting the topographic difference in the profile, it is observed that the decrease of elevation with closely spaced folding toward Andimeshk city indicates the reduction of tectonic rates in the area. The profile shows that possibly the subduction stopped in high Zagros and transmitted to the Zagros Fold Belt which indicate that orogeny migrated to the south west of the Zagros.

However, from the net erosion rate analysis, it reveals that the erosion process in the study area is not only depended on the uplifting but also influenced by the resistance of rock types. In the present study, it has been seen that the Asmari limestone of
Oligocene age and Gachsaran Formation of Miocene-Eocene age, which were dominated by gypsum are more subjected to erosion processes during time.

4-5- Discussions

The river profile of the study area is predicted approaching a graded and step like profile, indicated that the area has been tectonically disturbed. An increase in SL values resulted as a sign of elevated tectonic activity. The study demonstrated the existence of active deformation in the Zagros Structural Belt, as indicated by: (1) sinuosity values close to one; (2) steeper gradients and higher relief in the zone of rapid rock uplift; and (3) low to moderate resistance to erosion in areas with low relief features.

The erosion process in the study area is affected not only on by uplift but also by the differential resistance of rock types to erosion. In the present study, the Oligocene Asmari limestone and the Miocene–Eocene Gachsaran formation (dominated by gypsum) have been subjected to intensive erosion over time. Field data indicated that net erosion rates in the Sanandaj-Sirjan Zone is less than in the Zagros Fold Belt, and that the rate of uplift in the Zagros Fold Belt has been greater than in Sanandaj-Sirjan Zone over geologic time.

Also on the basis of topographic profiles and the variation in peak elevation between the two lithotectonic zones, it is proved that the Zagros Structural Belt is deformed not only because of tectonic processes and uplift, but also that of high rate of erosion.
generated high relief surface, rugged and immature topography. Hence, net erosion rates in the Zagros Fold Belt are lower than the rate of uplift, which can account for the more rugged and immature topography than in the Sanandaj-Sirjan Zone. The study also shows that net erosion rates varied from 10 m/m.y to about 162.5 m/m.y. The profile of the Dez River indicated that the most active tectonic zone falls in folded Zagros, where stream gradient indices vary from 806 meters to 165 meters. It is also apparent that the reduced gradient in the direction of the Dezful Embayment reduced the level of tectonic activity.

The study of the profiles combined with a field visit show that net erosion rates in Sanandaj-Sirjan Zone is less than the Zagros Fold Belt. It is also estimated that the rate of uplifting in Imbricate Zone and Zagros Fold Belt is greater than the rate of uplifting in Sanandaj-Sirjan Zone during the geological time scale. Also on the basis of topographic profile the variation in peak of two lithotectonics show that the Zagros Structural Belt is affected by tectonic uplift, but also it is controlled by erosion of differential nature. Hence, the net erosion rate in the Zagros Fold Belt is lower than the rates of uplift as compared to Sanandaj-Sirjan Zone. Erosion is also responsible for changing the topography of the area therefore it has affected the drainage systems. The topography profiles of the study area indicated that folding and faulting have acted as main controlling factors for flow direction of the streams. The faulting and fractures are responsible for the generation of trellis drainage patterns.

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. The results generated confirm the utility of the joint application of remote sensing analysis,
digital elevation modeling, and modern GIS techniques for studies in regional tectonic geomorphology.

This study has interpreted the tectonic geomorphology of the Zagros Structural Belt with the help of a DEM, augmented by ground truth work in the field visit and GIS/remote sensing techniques. For the purpose of tectonic interpretation of the study area, different geomorphic maps in a GIS environment were produced.

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