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IDENTIFICATION OF POSSIBLE ACTIVE TECTONICS AT AL-AJEEJ VALLEY DRAINAGE BASIN, NW IRAQ, USING GIS TECHNIQUE

Luay D. Yousif

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ABSTRACT

Al-Ajeej valley drainage basin is located in the northwestern part of Iraq. Tectonically, it is in the Al-Jazira Subzone, within the Mesopotamian Foredeep of the Unstable Shelf of the Arabian Platform. This basin is filled by the soft sediments of the Quaternary Period overlie the clastics of the Injana Formation of Late Miocene age. The entire Al-Ajeej basin is comprised of three contiguous sub-basins namely; Al-Badee, Al-Khazrajia and Al-Hamal sub-basins which occupy 80% of the northern and southeastern parts of the basin. The drainage network of the entire Al-Ajeej basin is delineated using the Digital Elevation Model (DEM) 30 m resolution of Iraq, to examine the influence of tectonic activity through an analysis of the geomorphic characteristics by the benefit of the hydrology tools in the geographic information system (GIS). The analyzed indices are; the Asymmetry Factor (***Af***), Stream Length, Gradient Index (***Sl***), Hypsometric Integral (***Hi***), Basin Shape (***Bs***), Valley Floor Width to Valley Height ratio (***Vf***) and Mountain Front Sinuosity (***Smf***). These six indices were classified and combined to yield the “Relative Active Tectonics” Index (***Iat***).

According to the (***Iat***) results, the entire Al-Ajeej basin and its three subbasins were classified as “**High”** to **“Moderate**” active tectonics. These results are due the effects of the existence of Sinjar Anticline in the northern most part of the basin and the subsurface extensional structural features. The tectonic activity of Al-Ajeej basin and its sub-basins are reduced to the class of "**Moderate"** active tectonics, because most of the basin area (about 90%) are filled by soft sediments of the Quaternary Period and the low-resistance clastics of the underlying Injana Formation, in addition to the plain topography and arid climate conditions, despite the effects of Sinjar structure and the subsurface structural features.

دراسة النشاط التكتوني المحتمل في حوض تصريف "نهر العجيج"، شمال غرب العراق باستخدام نظام المعلومات الجغرافية (GIS)

لؤي داود يوسف

المستخلص

حوض تصريف وادي العجيج يقع في الجزء الشمالي الغربي من العراق. تكتونيا يقع في نطاق الجزيرة في مقدمة حوض مابين النهرين للدرع غير المستقر من الصفيحة العربية. هذا الحوض مملوء بالترسبات الرخوة والضعيفة للعصر الرباعي وفتاتيات تكوين إنجانة (بعمر المايوسين المتأخر) الذي تحتها. حوض العجيج تشارك في تكوينه ثلاثة أحواض ثانوية هي البادية والخزرجية والحمال، والتي تحتل الأجزاء الشمالية والشرقية وتمثل (80%) من الحوض الكلي، ترتبط

Retired Senior Chief Geologist, e-mail: luaygeo@yahoo.com; luayalobaidy1955@gmail.com

مع بعضها في وسط الحوض لتكون مجرى وادي العجيج الرئيس. تم تحديد شبكة التصريف لكل حوض العجيج باستخدام نموذج الإرتفاعات الرقمية (Dem) بدقة 30 متر، لدراسة تأثير النشاط التكتوني للحوض من خلال تحليل خصائصه الجيومورفولوجية بالإستفادة من أداة الهيدرولوجي في نظام المعلومات الجغرافية (GIS). تم دراسة وتصنيف المعاملات الأتية: معامل التماثل (***Af***) ونسبة طول مجرى النهر الى إنحداره (***Sl***) ومنحنى الهيبسوميتري (***Hi***) ودالة شكل الحوض (***Bs***) ونسبة عرض قاع النهر الى إرتفاعه (***Vf***) ثم دالة تعرج وانثناء واجهة الجبل (***Smf***)، ثم صنفت كل دالة الى ثلاثة أصناف. بعد ذلك تم جمع أصنافهم للحصول على دالة النشاط التكتوني النسبي (Iat) للحوض. على أساس نتائج دالة (Iat) تم تصنيف حوض العجيج وأحواضه الثانوية على أنها "**عالية**" الى "**متوسطة**" النشاط التكتوني. تعود هذه النتائج الى العوامل التركيبية والصخارية المسيطرة، حيث طية سنجار المحدبة (في أقصى شمال الحوض) والظواهر التركيبية تحت السطحية (في بقية أجزاء الحوض)، علاوة على الترسبات الضعيفة التي تملأ أغلب مساحة الحوض. ان تأثير النشاط التكتوني لحوض العجيج وأحواضه الثانوية قد تقلص الى صنف "**متوسط**" النشاط التكتوني لكون أغلب أراضيه (أكثر من 90%) مملؤة بالترسبات الرخوة الضعيفة لترسبات العصر الرباعي والصخور الفتاتية لتكوين إنجانة، إضافة الى الطوبوغرافية المنبسطة والمناخ الجاف للمنطقة، بالرغم من تأثير طية سنجار والمظاهر التركيبية تحت السطحية.

INTRODUCTION

The aim of the present work is to study the tectonic geomorphology of the catchment of the Al-Ajeej basin area. The Al-Ajeej drainage basin is located in Al-Jazira, within Nineva Governorate, northwest Iraq. It is limited by the following coordinates; Longitudes; 41º 10' – 42º 00' East and Latitudes; 35º 20' – 36º 25' North, as shown in the Fig. (1). The drainage basin has a catchment area of 3805.6 Km², perimeter equal to 819.8 Km, length about 91.8 Km and elevations between 200 to more than 1300 m above sea level.

The entire Al-Ajeej drainage basin includes three sub-basins; Al-Badee, Al-Khazrajia and Al-Hammal, occupy the northern, northeastern and the southeastern parts respectively, about 80% of the whole main Al-Ajeej basin. The main trunks of these three sub-basins are jointed together in the center of the basin to form the main trunk of the valley, which runs in the remained southern part of Al-Ajeej drainage basin. The main branches, which drain from the southern flank of Sinjar Anticline, have different trends. The tributaries of; Al-Badee subbasin, flow NNW – SSE direction, Al-Khazrajia sub-basin flow N – S trend, while the tributaries of; Al-Hammal subbasin and the southwestern parts of Al-Ajeej basin, flow NE – SW direction (Al-Taiee and Rasheed, 2011).

Geomorphic indices are useful tools for understanding the evolution of tectonic and non-tectonic landforms, nature of deformation, uplift and valley degradation (Raj *et al*., 2003). Studying tectonic activity depends on the use of geomorphological indicators that are sensitive to a number of variables, such as rock resistance, climate changes and tectonic processes (Bhat *et al*., 2013). The results of geomorphic indicators show the extent of area affected by tectonic activity on one hand and the extent of acceleration of geomorphological processes including erosion and deposition on the other hand. In geomorphology, the traditional use of the geographic information system (GIS) capabilities can be found in multi-criterion analyses works that require the combination of different spatial data in conjunction with statistical analyses (Pérez-Peña *et al*., 2010).

The drainage network of the entire Al-Ajeej basin is delineated using the Digital Elevation Model (DEM) 30 m resolution, to examine the influence of tectonic activity through an analysis of the geomorphic characteristics using the hydrology tools in the Geographic Information System (GIS). The analyzed indices are; Asymmetry Factor (***Af***), Stream Length-Gradient Index (***Sl***), Hypsometric Integral (***Hi***), Basin Shape (***Bs***), Valley Floor Width to Valley Height ratio (***Vf***) and Mountain Front Sinuosity (***Smf***). Then, these six indices were classified and combined to yield the “Relative Active Tectonics” Index (***Iat***).

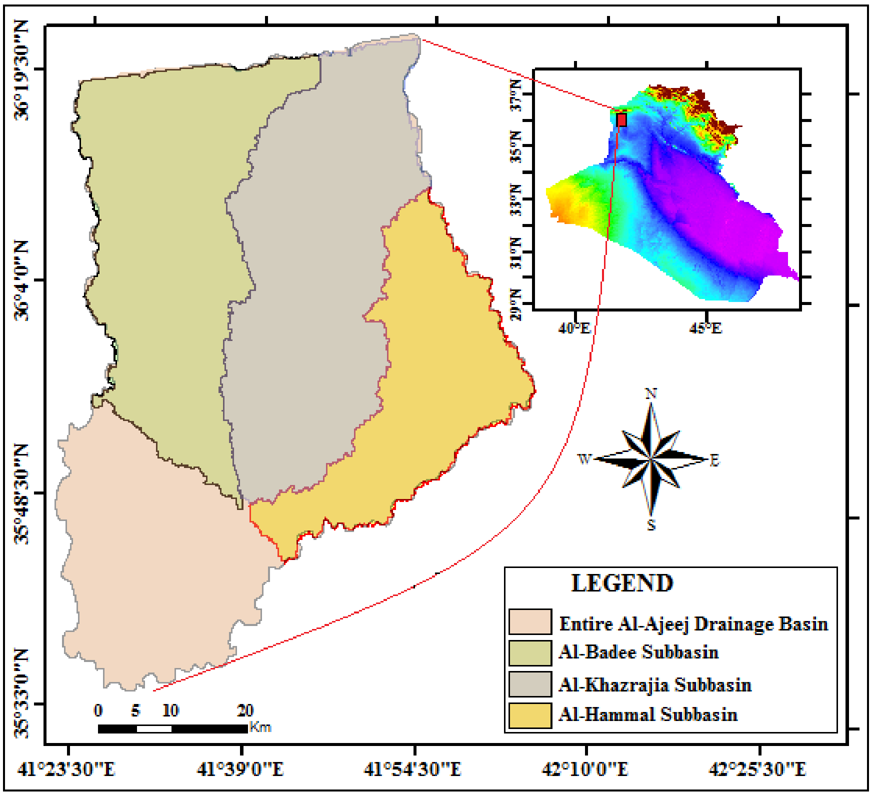

Fig.1: Location map of the entire Al-Ajeej drainage basin and its three sub-basins

- **Previous Works**

- Sissakian and Dikran (1998) showed that Al-Jazira area, is uplifted by amount of (200 – 250) m, with estimated rate of uplift (0.1 – 0.2) cm/100year.
- Fouad and Nasir (2009) described the tectonic and structural evolution of Al-Jazira area, where Al-Ajeej valley drainage basin is located, using seismic, drill-hole and surface geological data. They denoted to a network of subsurface extensional structures are dominated in the area. These intercontinental structures are mainly ENE – WSW and NW – SE trending grabens and normal faults.
- Sissakian *et al*. (2015) reported that three terrace levels are present along Wadi Al-Ajeej beside other two levels on the top of Sinjar Mountain, where the ancient JughJugh River was crossing the mountain. However, tectonic forces and growing of Sinjar anticline have shifted the main course of JughJugh River and separate it into two parts, the southern one is called Wadi Al-Ajeej. The main trend of the nowadays Wadi Al-Ajeej is ENE – WSW, which is the main trend of grabens and faults (Fouad and Nasir, 2009). Most probably it runs following the trace of a subsurface structure, which is located between Khlaisia Graben and Tel Hajar subsurface anticline.
- Yousif (2019) computed and determined the morphometric parameters such as linear, aerial and relief aspects of the Al-Ajeej Drainage basin, using Dem-30 m resolution in GIS environment. The study showed that three subbasins named as; Al-Badee, Al-Khazrajia and Al-Hammal are conjugated to form the northern and the southeastern parts (80%) of the entire Al-Ajeej drainage basin, with 6th orders stream network. The bifurcation ratio in all sub-basins has experienced moderate structural disturbances, by "Tel-Hajar" subsurface extensional structure, that change the main streams flow from NNW – SSE to NNE – SSW.

GEOLOGY OF Al-AJEEJ VALLEY DRAINAGE BASIN

Al-Ajeej valley is one of the main valleys in the Jazira Plain with a trend of NNE – SSW for the main valley, however, the main branches, which drain from the southern flank of Sinjar anticline; west of the longitude 41^{O} 40' N have trend of NNW – SSE (Sissakian *et al*., 2015).

In Iraq, Al-Ajeej valley drainage basin consists of three main branches (Al-Badee, Al-Khazrajia and Al-Hamal) which originate from the southern limb of Sinjar anticline. They extend between the water divide of Al-Khabour basin to the west and Al-Tharthar basin to the east (Al-Taiee and Rasheed, 2011) and combined to form the main Al-Ajeej valley. Most probably they run following the trace of a subsurface structure, which is located between Khlaisia Graben to the south (out of the basin) and Tel Hajar subsurface anticline northwest the basin (Sissakian *et al*., 2015).

Geomorphologically, Al-Ajeej drainage basin is classified as plain land except some high lands of Sinjar anticline at the north of the basin (Ma'ala, 2009 and Yacoub *et al*., 2012). Many of the structural – denudational units are represented within Al-Ajeej drainage basin, such as; Plateau of Al-Ba'aj plain is developed where the strata of the exposed Injana Formation are more or less horizontal. This plateau occupies a wide area of Al-Ajeej basin, over the pediment and Al-Ba’aj plain. Structural ridge of the Sinjar anticline extends along the northern part of this basin with more than 1300 m a.s.l. Hogbacks are developed where the strata dip steeply at 40º plus (Huggett, 2007). These hogbacks are developed on the homoclinal ridges along the southern slopes of the Sinjar Mountain (Ma'ala, 2009 and Yacoub *et al*., 2012).

Denudation units are developed as Pediment and Badlands. Pediment is well developed in Al-Ba'aj plain, which occupies the area between foot slopes of the Sinjar Mountain. It is characterized by gently inclined dissected erosional surface. Badlands are well developed on the dissected slopes of the banks of Wadi Al-Ajeej, due to the alternation of hard and soft rocks of Fatha and Injana formations (Ma'ala, 2009).

Among the units of fluvial origin River Terraces is the main well developed unit along Al-Ajeej valley. Three levels are identified: (15 – 25) m, (30 – 40) m and (50 – 60) m; above the present valley floor respectively (Ma'ala, 1976). Other units of fluvial origin include infilled valleys, depression fill sediments and alluvial fans (Sissakian *et al*., 2015). Units of Evaporation Origin, such as Calcrete, cover the southwestern part of the extreme northern part of the basin ranging in thickness between (0.25 – 0.5) m. The gypcrete covers many parts in the studied area, top of hills and mesas and partly their slopes (Sissakian *et al*., 2015). Forms of Aeolian Origin are developed as Sand Dunes and Nabkhas. These landforms have wide spread throughout the area.

Stratigraphically, the Injana Formation of Late Miocene age, is the only exposed rock formation in the Al-Ajeej drainage basin, at the southwestern part. It exposed at the base of the main Al-Ajeej valley and consists predominantly of red, brown and grey claystone, siltstone and sandstone (Ma'ala, 1976).

Different types of Quaternary sediments cover unconformably the outcrops of the Injana Formation with variable thicknesses range from few centimeters up to 10 m. Three main genetic types of Quaternary sediments were differentiated; these are:

1. Alluvial Sediments such as river terraces, alluvial fan and sheet runoff sediments.

2. Slope Sediments, are developed in the southwestern area of the basin. The thickness ranges from (0.5 – 1.5) m.
3. Residual soil of sandy silty soil covers the majority of the northern part of the area, with variable thicknesses (0.5 – 3 m).

Tectonically, the studied area is located within Al-Jazira Subzone, of the Mesopotamia Foredeep, which is a part of the Outer Platform (Unstable Shelf) of the Arabian Plate (Fouad, 2012). It is dominated by a network of subsurface extensional structures. These structures are mainly ENE – WSW and NW – SE trending grabens and normal faults (Fouad, 1997, 1998 and Nasir, 2001). From neo-tectonic point of view, the Jazira Area, in which the studied basin is located, is uplifted by amount of (200 – 250) m, with estimated rate of uplift (0.1 – 0.2) cm/ 100 years (Sissakian and Deikran, 1998). Tel-Hajar structure, is a subsurface structure, occurs at the northwestern part of the basin trending SW – NE. It is an inverted half graben bounded by one major boundary fault (Fouad and Nasir, 2009).

METHODOLOGY

Some of the geomorphic indices are most useful in studies of active tectonic (Sarp *et al.*, 2010). Indices of active tectonics may detect anomalies in the fluvial system or along mountain fronts. These anomalies may be produced by local changes from tectonic activity resulting from uplift or subsidence (El-Hamdouni *et al.*, 2008).

The current work is carried out in order to identify and quantify the possible active and neo-tectonic deformation in Al-Ajeej drainage basin. The main objective of the study was fulfilled by computing the geomorphic indices to delineate the possible tectonic activity of the studied basin, using GIS and remote sensing techniques. The digital elevation model (DEM) with 30 m spatial resolution, of Iraq territory, is used as a base map in Arc GIS 9.3 software, to extract the stream networks and their stream orders according to Strahler (1957). Then the drainage basin stream network (Fig.2) is delineated and the three main sub-basins, namely; Al-Badee, Al-Khazrajia, Al-Hamal in addition to the entire Al-Ajeej basin are analyzed.

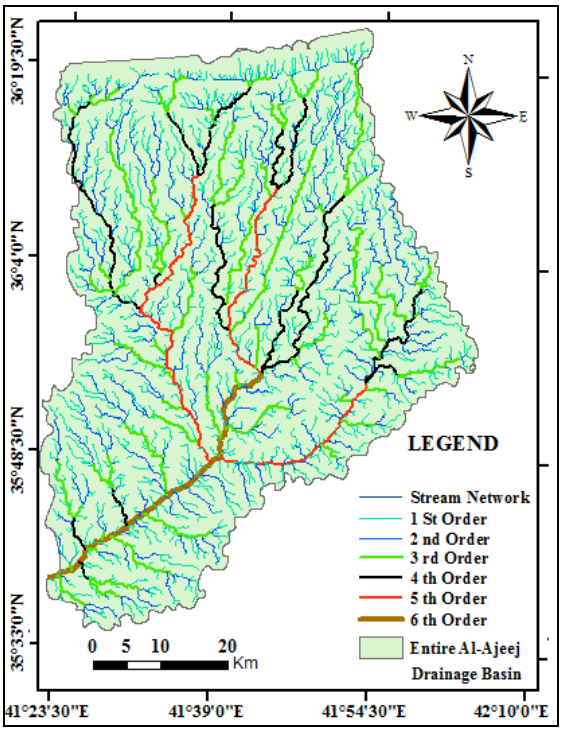

Fig.2: Stream network of the Al-Ajeej drainage basin

In order to evaluate the rate of tectonic activity, geomorphometric indices such as the Asymmetry Factor (*Af*), Hypsometric curve and Hypsometric Integral (*Hi*), Valley Floor Width to Height Ratio (*Vf*), stream length-gradient (*Sl*), Basin Shape (*Bs*) and Mountain Front Sinuosity (*Smf*) are analyzed. These six geomorphic indices are calculated, and the results of each one are divided into three classes. Then, the relative tectonic activity is calculated, and their values are classified and analyzed in four groups. The basin area, length and perimeter of the four sub-basins are identified through an extension called Arc hydrology tools in Arc GIS software using DEM as input and listed in Table (1).

Table 1: Characteristics of Al-Ajeej drainage basin

Subbasin	Al-Badee	Al-Khazrajia	Al-Hamal	Al-Ajeej
Area (Km^2)	1235.4	1122.4	690.2	3805.6
Perimeter (Km)	240.3	212.6	213.4	819.8
Length (Km)	65.6	62.6	59.9	91.9

RESULTS AND DISCUSSION

Geomorphic indices applicable to fluvial systems in different regions and of varying size correlate with independently derived uplift rates (Kirby and Whipple, 2001) and are applicable to a variety of tectonic settings where topography is being changed (Bull and McFadden, 1977; Azor *et al*., 2002). The present study is based on the calculation of six geomorphic indices for the above mentioned four sub-basins of the Al-Ajeej drainage basin. The results of analyzed geomorphic indices of Al-Ajeej basin are discussed in the following sections.

- **Asymmetry Factor (*Af*)**

This index is related to tectonic and non-tectonic factors. Non-tectonic factors may relate to lithology and rock fabrics. Tectonic is a way to evaluate the tectonic tilting at the scale of a drainage basin (Hare and Gardner, 1985; Keller and Pinter, 2002).

To calculate this index in the area, ***At*** and ***Ar*** are obtained using the subbasins and the master river maps. The index is defined as follows (Hare and Gardner, 1985; Keller and Pinter, 2002):

$$Af = \frac{Ar}{At} * 100 \quad \text{......................................} \quad (1)$$

Where;
***Ar**:* is the right-side area of the master stream basin (looking downstream),
***At**:* is the total area of the basin.

Af is close to 50 (when symmetry) if there is no or little tilting perpendicular to the direction of the master stream. ***Af*** is significantly greater or smaller than 50 under the effects of active tectonics or strong lithological control. The values of this index are divided into three categories (Arian and Aram, 2014).

Class 1 ($Af < 35$ or $Af > 63$), Class 2 ($57 < Af < 65$ or $35 < Af < 43$) and
Class 3 ($43 < Af < 57$)

Values under and over 50% represent rightward and leftward tilting (according to the main stream flow), respectively. The values of this index are divided into three categories. If the value of ***Af*** is under 35 and more than 65 then the watershed is fall in class 1 category and class 2 category is considered as when the ***Af*** value is somewhere in the range of 57 and 65 or between 35 and 43 while the value of ***Af*** ranges from 43 to 57 is considered as class 3 category (Arian and Aram, 2014).

In Al-Ajeej sub-basins, the minimum value of the calculated ***Af*** is 38.26 in Al-Khazrajia subbasin, while the maximum value is 75.77 in Al-Badee sub-basin (Table 2). ***Af*** values of Al-Badee and Al-Khazrajia sub-basins are so far from the symmetry which indicate the tilting assuming the tectonic activity caused a left and right dipping respectively. These are very clear as shown in Fig. (3).

Table 2: Asymmetry Factor (***Af***) of Al-Ajeej Sub-basins

Subbasin	Al-Badee	Al-Khazrajia	Al-Hamal	Al-Ajeej
Af	75.77	38.26	49.13	51.98
Class	2	2	3	3
Activity	Moderate	Moderate	Inactive	Inactive

Af value of Al-Badee sub-basin indicate leftward (> 50) dipping, which is very clear on the shorter tributaries to the left of the main stream compared to the right side tributaries, whereas ***Af*** value of Al-Khazrajia sub-basin show rightward (< 50) dipping made the right tributaries longer than the left ones (Fig.3), whereas ***Af*** values of Al-Hamal sub-basin and the Al-Ajeej sub-basin are close to the symmetry (50), which indicate low or no tilting (Fig.3).

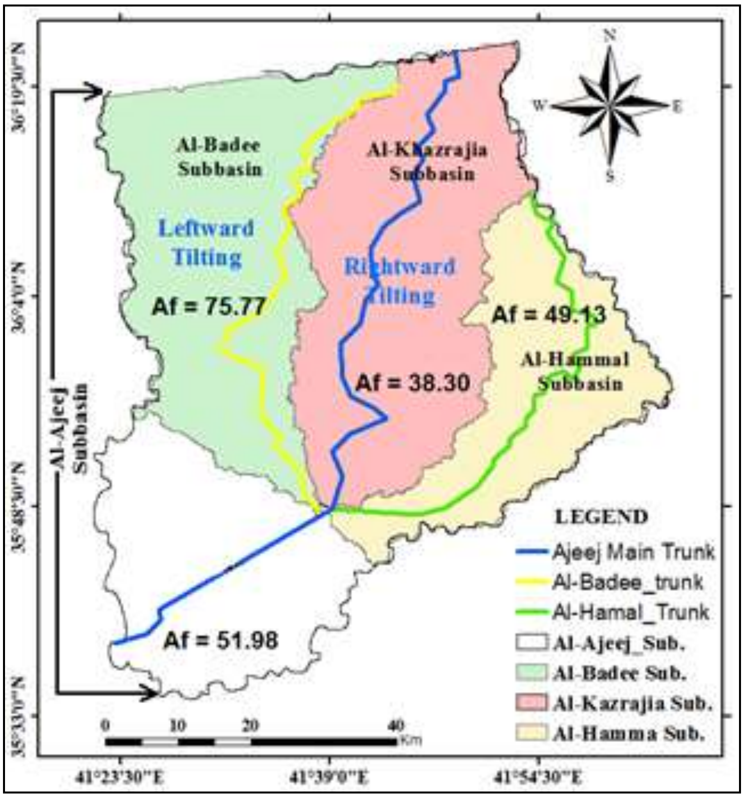

Fig.3: ***Af*** factor values of the studied sub-basins

- **Stream Length – Gradient Index (*Sl*)**

Rivers flow over rocks and soils of various strengths tend to reach equilibrium with specific longitudinal profiles and hydraulic geometrics (Hack, 1973; Bull, 2007). Hack (1957, 1973 and 1982) defined the ***Sl*** index to discuss the influence of environmental variables on longitudinal stream profiles and to test whether stream has reached equilibrium or not. Mathematically, ***Sl*** is given by:

$$Sl = (\Delta H / \Delta L) * L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where;

ΔH: is the change in elevations of the reach,

Δ***L***: is the length of the reach

L: is the total channel length from the midpoint of the reach of interest upstream to the highest point on the channel, and

(***ΔH/ΔL***): is the channel slope or gradient of the reach (Keller and Pinter, 1996).

The high values of ***Sl*** index present where rivers cross hard rocks and reflect relatively high tectonic activity. Alternatively, low values of ***Sl*** index indicate relatively low tectonic activity and suggest less-resistant and softer underlying rock types (Hack, 1973; Keller and Pinter, 2002). Also, the anomalous ***Sl*** values that are observed in uniform lithological conditions are due to tectonic activities. The ***Sl*** index value will increase as rivers and streams flow over an active uplift, and may have lesser values when they are flowing parallel to features such as valleys produced by strike-slip faulting (Keller and Pinter, 2002).

The values of ***Sl*** index are divided into three categories according to El-Hamdouni *et al*., (2008): Class 1 (***Sl*** ≥ 500); Class 2 (300 ≤ ***Sl*** < 500); and Class 3 (***Sl*** < 300).

For the current study, all the calculated ***Sl*** values are less than 300 within class 3 (Fig.4), indicating inactive tectonics, due to the low resistance and soft underlying rock types of the Injana Formation and the Quaternary clastic sediments.

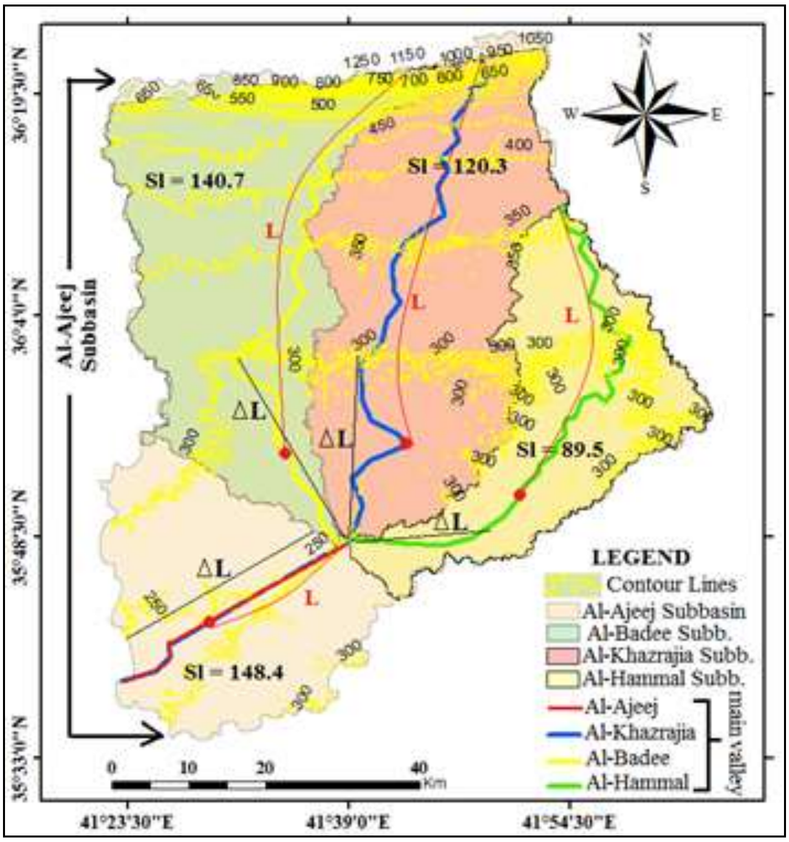

Fig.4: Stream length- gradient index (***Sl***) of the Al-Ajeej Sub-basins

Generally, Table (3), shows the low values of ***Sl*** of Al-Ajeej basin and its sub-basins (***Sl*** < 300) within class 3. This is may be due to; the main stream channels cross through soft sediments of the Quaternary Period and low resistance subsurface bedrock of Injana Formation which is composed of sandstone, siltstone and claystone that made the erosion processes overcome the tectonic activity.

Table 3: Stream length-gradient (***Sl***) factor values of the subbasins

Subbasin	Al-Badee	Al-Khazrajia	Al-Hammal	Al-Ajeej
(*Sl*) values	140.7	120.3	89.5	148.4
Class	3	3	3	3
Activity	Inactive	Inactive	Inactive	Inactive

- **Hypsometric curve and Integral (*Hi*)**

The hypsometric curve (***HC***) and hypsometric integral (***Hi***) are indices that describes the distribution of elevation of a given area of a landscape. Hypsometric curve (***HC***) is obtained by plotting the relative area (a/A) on abscissa (x-axis) and relative elevation (h/H) on ordinate (y-axis) (Barman *et al*., 2017). The relative area is calculated as a ratio of the area above a particular contour (a) to the total area of the sub-watershed above outlet (A), while the relative elevation is obtained as the ratio of the height of a given contour (h) from the base plane to the maximum basin elevation (H) (Ritter *et al*., 2002) . The hypsometric curve is related to the volume of the soil mass in the basin and the amount of erosion that had occurred in a basin against the remaining mass (Hurtez, *et al*., 1999).

Hypsometric curve (***HC***) of younger landscape is characterized be convex upward curve and its ***Hi*** tend to be 1.0, mature landscape with S-shaped ***HC*** (concave upwards to high elevations and convex downward at low elevations) refers to moderate erosion, while for older or peneplain or distorted landscape has concave upward ***HC*** (Fig.5) and ***Hi*** tend to be 0.0 (Keller and Pinter, 2002).

Accordingly, the ***HC*** shape of all the four studied sub-basins have the concave upward indicating old stage landscape and highly eroded area (Fig.6), while Al-Hammal sub-basin with has ***HC*** of S-shape, indicating maturity stage and moderately eroded region.

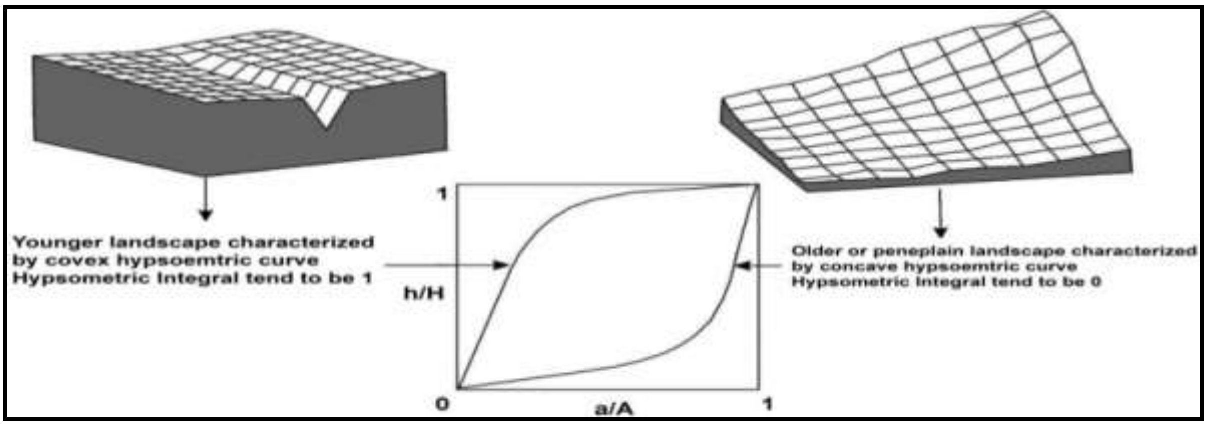

Fig.5: Hypsometric curve of young and old river stages
(Singh *et al*., 2008)

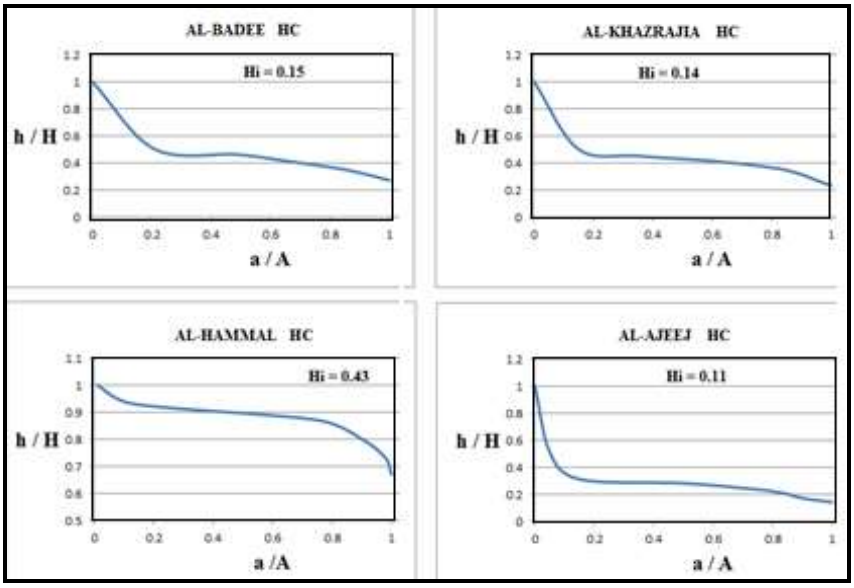

Fig.6: Hypsometric curves of the studied sub-basins

The Hypsometric integral (***Hi***) is also an indication of the cycle of erosion (Strahler, 1952 and Garg, 1983). The cycle of erosion is the total time for reduction of land area to the lowest level. The hypsometric integral is calculated by the following formula (Keller and Pinter, 2002):

$$Hi = \frac{(H\ mean - H\ min.)}{H\ max. - H\ min.)} \dots\dots\dots\dots\dots\dots\dots\dots \quad (3)$$

Where; Hmean, Hmin and Hmax represent the mean, minimum and maximum elevations, respectively, calculated from the DEM.

Strahler (1952) described the values of ***Hi*** on the basis of the erosional status (cycle of erosion) of the basin into three stages; If, ***Hi ≤ 0.3*** (old-age stage or monadnock), it means the basin is fully stabilized and characterized by landscapes near base level with very subdued relief. ***0.3 ≤ Hi ≤ 0.6*** (equilibrium or mature stage) indicate watershed is susceptible to erosion and has sigmoidal shaped HC. ***Hi > 0.6*** (inequilibrium or youthful topography) means the basin is highly susceptible to erosion by deep incision and rugged relief.

Ali *et al*. (2017) stated that hypsometric analysis provides useful information for understanding the geomorphic development of a basin. It may reflect the interaction between tectonics and erosion processes. Differences in the shape of the curve and the hypsometric integral value are related to the degree of disequilibria in the balance of erosive and tectonic forces (Weissel *et al*., 1994). High values of the ***Hi*** are possibly related to young active tectonic and low values are related to older landscapes that have been more eroded and less impacted by recent active tectonics (El-Hamdouni *et al*., 2008).

Table (4) and Fig.(7) show that the hypsometric integral (***Hi***) values of the Al-Badee, Al-Khazrajia and Al-Ajeej sub-basins are low and relatively close to (0.0), while Al-Hammal sub-basin has an intermediate (***Hi*** = 0.43) value, all of them, indicating equilibrium (old stage) and mature stage and highly susceptible to laterally erosion area (less down cutting) (Keller and Pinter, 2002 and Pérez-Peña *et al*., 2010).

Table 4: Hypsometric integral values of the studied sub-basins

Subbasin	Al-Badee	Al-Khazrajia	Al-Hammal	Al-Ajeej
(*Hi*) values	0.15	0.14	0.43	0.11
Class	1	1	2	1
Activity	Inactive	Inactive	Moderate	Inactive

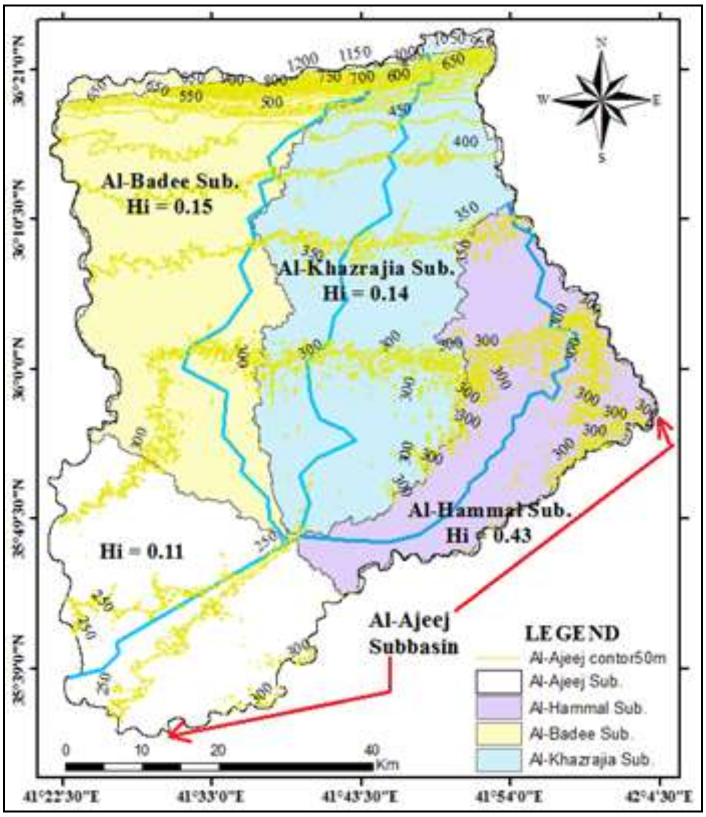

Fig.7: ***Hi*** values maps of Al-Ajeej drainage basin and its subbasins

- **Basin Shape Index (*Bs*)**

Drainage basin shape is an elongation ratio and describes the planimetric shape of a basin. It is expressed as:

Bs = Bl / Bw ………………… (4)

Where ***Bs*** is the basin shape, ***Bl*** is the length of the basin measured from headwaters to the mouth of the basin and ***Bw*** is the width of the basin (Cannon, 1976; Ramirez-Herrera, 1998 and El-Hamdouni *et al*., 2008).

The index reflects differences between elongated basins with high values of ***Bs*** associated with relatively higher tectonic activity, and more circular basins with low values generally associated with low tectonic activity. Relatively young drainage basins in active tectonic areas tend to be elongated in shape normal to the topographic slope of a mountain. With continued evolution or less active tectonic processes, the elongated shape tends to evolve to a circular shape (Bull and McFadden, 1977).The values were classified into three categories: **1** (***Bs* > *3***), **2** (***2* < *Bs* < *3***) and **3** (***Bs* < *2***) according to Ramirez-Herrera (1998).

Table (5) shows that, Al-Badee sub-basin has high ***Bs*** value with elongated shape, while Al-Khazrajia and Al-Hammal sub-basins have moderate values (Class 2) and close to the high class (class 1) with elongated shapes indicating tectonic activity due the Sinjar Structure development. Whereas, Al-Ajeej main basin is within class 3, close to circular shape, which indicates less active tectonic processes. It is worth noticing that ***Bs*** values of both Al-Khazrajia and Al-Hammal sub-basins are close to class 1 of active tectonics.

Table 5: ***Bs*** values of the studied sub-basins

Subbasin	Al-Badee	Al-Khazrajia	Al-Hammal	Al-Ajeej
***Bl* (Km)**	63.22	64.91	59.57	92.05
***Bw* (Km)**	18.8	21.73	20.21	54.1
(*Bs*) values	3.36	2.99	2.97	1.7
Basin Shape	Elongate	Close to Elongated	Close to Elongated	Close to Circular
Class	1	2	2	3
Activity	Active	Moderate	Moderate	Inactive

- **Ratio of valley floor width to valley height (*Vf*)**

The ***Vf*** ratio is a good measure that indicates whether the river is actively down cutting and incising (Bull and McFadden, 1977). The index was originally used to distinguish V-shaped valleys from U-shaped valleys, where V-shaped valleys are common in areas of active uplift and deep, linear stream incision (low V*f* values, often close to 0). U-shaped valleys are representative of formerly glaciated or tectonically stable areas where stream valley bottoms tend to be wider (higher V*f* values) (Bull and Fadden 1977; Keller and Pinter 1996; Pérez-Peña *et al*., 2010). ***Vf*** is defined as the ratio of the width of the valley floor to its average height (Bull and McFadden, 1977; Bull, 1978) and is computed by equation (5) .

$$\boldsymbol{Vf} = 2\boldsymbol{Vfw} / [(\boldsymbol{Eld} - \boldsymbol{Esc}) + (\boldsymbol{Erd} - \boldsymbol{Esc})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where, ***Vf*** is the ratio of valley floor width to valley height; ***Vfw*** is the width of the valley floor; ***Eld*** is the elevation of the divide on the left side of the valley; ***Erd*** is the elevation on the right side; and ***Esc*** is the mean elevation of the valley floor. ***Vf*** values are divided into three classes: Class 1 ($Vf < 0.5 \rightarrow$ Active), Class 2 ($0.5 \leq Vf \leq 1 \rightarrow$ Moderate), and Class 3 ($Vf > 1 \rightarrow$ Inactive) according to Bull and McFadden, (1977).

For each of the studied sub-basin, the requisite ***Vf*** data are obtained along transverse valley profile and calculated at different segments of the main valley; up, mid and downstream. Table (6) and Fig. (8) show that the resulted ***Vf*** values of the upstream and midstream segments for the three sub-basins are less than 0.5 indicating prominent down cutting (V-Shaped) stream channels due to tectonic activity caused by the action of the structural feature of the Sinjar anticline and subsurface structural features. ***Vf*** values of the downstream cross sections are within Class 2 ($0.5 < Vf < 1.0$), indicating tectonic quiescence, where stream valley bottoms tend to be relatively wider and close to U-shape due to eroding laterally into the adjacent hill slopes. The mean values of ***Vf*** for each sub-basin are within class 1 (tectonically active) by the action of Sinjar anticline and the subsurface extensional structure.

Table 6: Vf values of the Al-Ajeej sub-basins

Subbasin	Al-Badee	Al-Khazrajia	Al-Hammal	Al-Ajeej
Upstream	0.11	0.10	0.42	0.10
Midstream	0.42	0.45	0.34	0.59
Downstream	0.55	0.91	0.59	0.73
Mean	0.36	0.49	0.45	0.47
Class	1	1	1	1
Activity	Active	Active	Active	Active

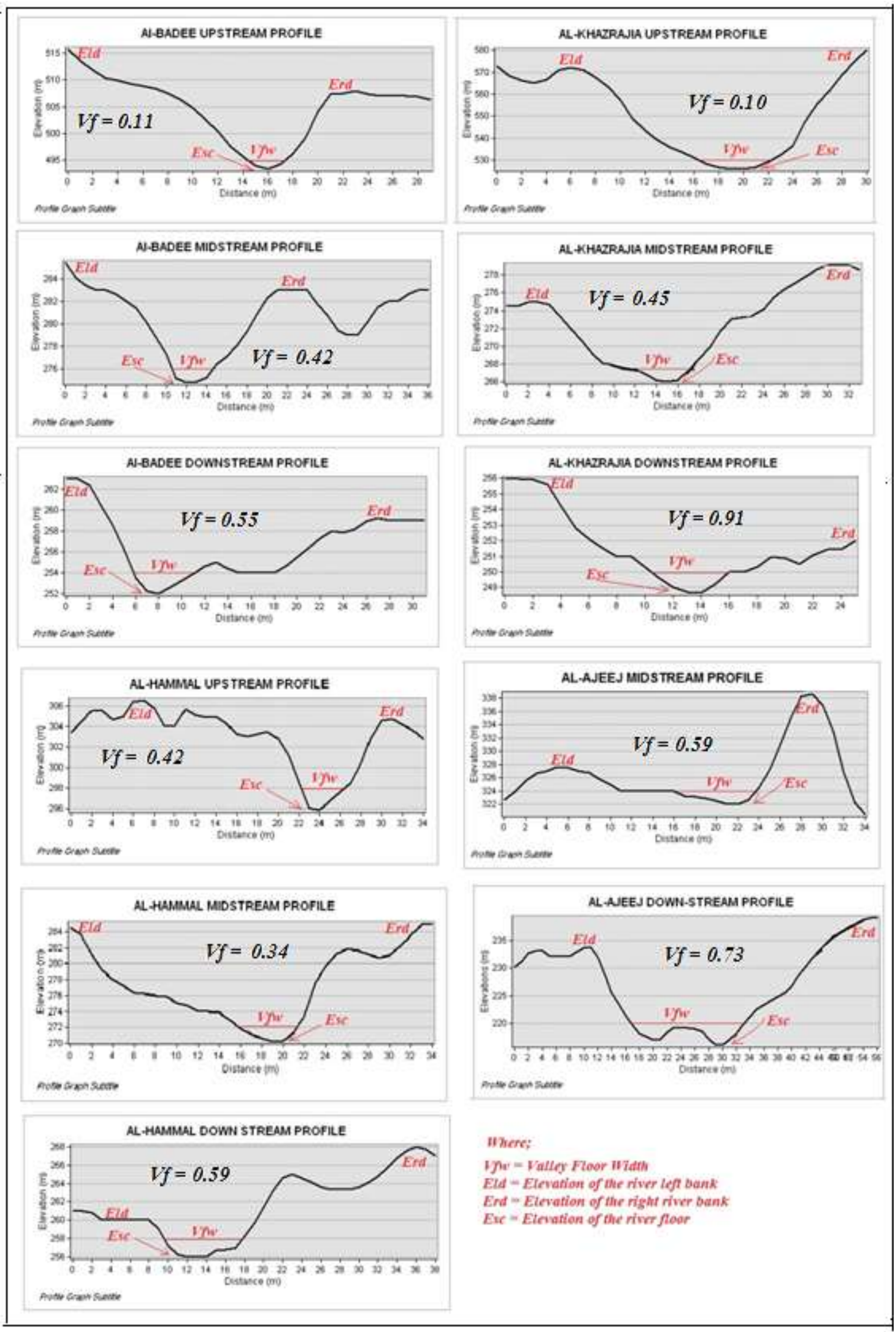

Fig.8: Cross section profiles along the main stream channels of Al-Ajeej sub-basins

- **Mountain Front Sinuosity Index (*Smf*)**

Mountain fronts sinuosity is an index that reflects the balance between erosional forces that tend to cut embayment into mountain front and tectonic forces that tend to produce a straight mountain front coincident with an active range bounding fault (Bull and McFadden, 1977). Those mountain fronts associated with active tectonics and uplift are relatively straight, with low values of ***Smf***. If the rate of uplift is reduced or ceases, then erosional processes will carve a more irregular mountain front, and ***Smf*** will increase. Mountain front sinuosity index is defined as (Bull and McFadden, 1977 and Bull, 1978):

$$Smf = Lmf / Ls \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where;
Smf : is the mountain front sinuosity,
Lmf: is the length of the mountain front along the foot of the mountain, and,
Ls: is the straight-line length of the mountain front.

The mountain front sinuosity (***Smf***) is commonly less than 3, and approaches 1.0, where the steep mountain rise rapidly along a fault or fold. Therefore, this index can play an important role in tectonic activity. Considering the fact that mountain-front sites are independent of sub-basin places, chances are that some of them have various fronts and that the others have no mountain fronts (Bull, 2007 in Arian and Aram, 2014). The sinuosity of highly active mountain fronts generally ranges from 1.0 to 1.5, while moderately active fronts range from 1.5 to 3.0, and that of inactive fronts ranges from 3 to more than 10. A sinuosity greater than 3 describes a highly-embayed front (Bull and McFadden, 1977). The ***Smf*** values are divided into three classes; Class 1 ($Smf < 1.5$), class 2 ($1.5 \leq Smf \leq 3$), and class3 ($Smf > 3$).

Thus, ***Smf*** index is calculated for the entire Al-Ajeej basin, Al-Badee and Al-Khazrajia sub-basins along the 600 m contour elevation, without Al-Hammal sub-basin because it has no mountain front (Fig.9). The 600m contour line is chosen, because it has very clear sinuosity (eroded mountain fronts) and it separates between the very steep slopes (Very dense contour lines) area and the relatively gentle slopes (relatively open spaced contour distance) area. All of the calculated ***Smf*** values are within class 2 of "**Moderate**" active tectonics (Table 7). This means that the rate of uplift is reduced, and then erosional processes have carved a more irregular mountain front.

Table 7: Mountain front sinuosity (***Smf***) values of Al-Ajeej basin subbasins

Subbasin	***Lmf*** (Km)	***Ls*** (Km)	***Smf*** (Km)	***Class***	***Activity***
Al-Badee	73.0	27.6	2.64	2	Moderate
Al-Khazrajia	33.2	17.25	1.92	2	Moderate
Al-Hammal	-	-	-	-	Inactive
Al-Ajeej	107.9	44.85	2.4	2	Moderate

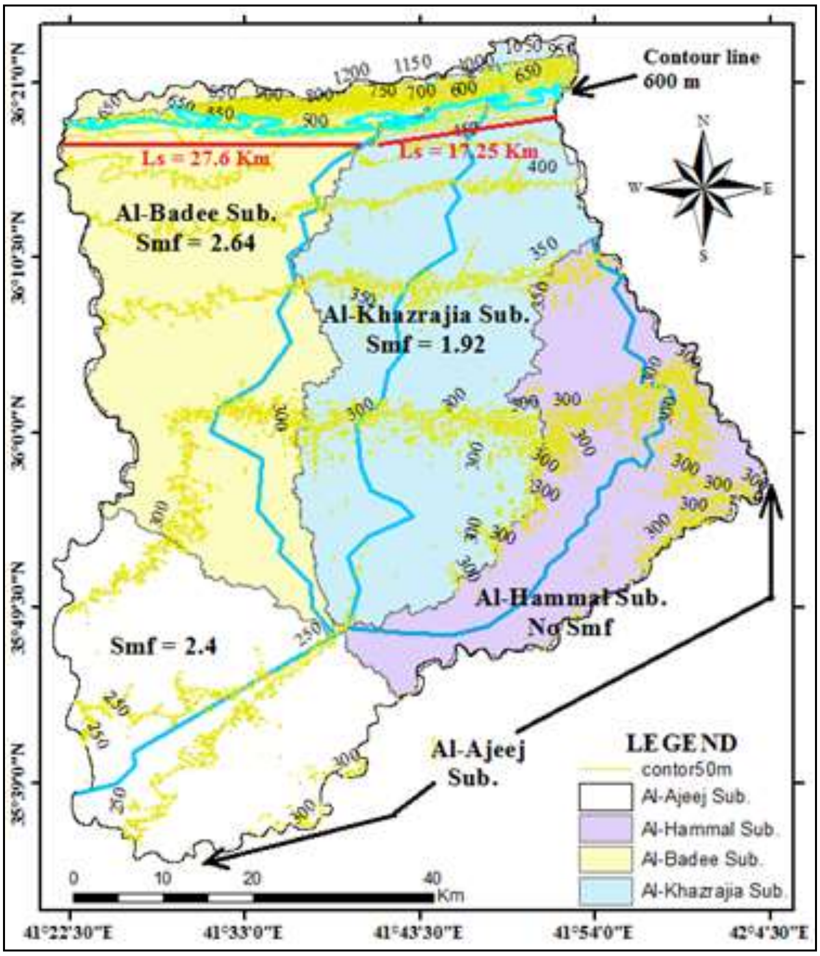

Fig.9: Mountain front sinuosity index (***Smf***) of the studied sub-basins

- **Relative tectonic activity classes**

The relative tectonic activity classes (***Iat***) are obtained by compiling all the six geomorphic indices. Based on the value of each geomorphic index, the indices are arbitrarily divided into three classes - class 1 with higher geomorphic index, class 2 with moderate index and class 3 with lower index (El-Hamdouni *et al*., 2008).

Relative tectonic activity classes (***Iat***) obtained by the average of the different classes of geomorphic indices and classified into four classes; Class I (1< ***Iat*** < 1.5) shows very high tectonic activity, class II (1.5 ≤ ***Iat*** < 2) shows high tectonic activity, class III (2 ≤ ***Iat*** ≤ 2.5) shows moderate tectonic activity and class IV (***Iat*** > 2.5) shows low or inactive tectonics (El-Hamdouni *et al*., 2008 and Mosavi and Arian, 2015).

According to the ***Iat*** values, the morphometric indices of Al-Ajeej sub-basins indicate the "High" and "Moderate" tectonic activity. The "High" classes of tectonic activity are in both of Al-Badee and Al-Khazrajia sub-basins (Table 8), resulted by the action of the tectonic control of Sinjar Anticline in the north. The moderate active tectonics in both of Al-Hammal and Al-Ajeej sub-basins is due to reduction of the effect of the Sinjar anticline by the action of the streams erosive processes as shown in Fig. (10).

Table 8: Relative active tectonic (***Iat***) classes of Al-Ajeej sub-basins

Subbasin	*Af*	*Sl*	*Hi*	*Bs*	*Vf*	*Smf*	*Iat value*	*Iat class*	*Activity*
Al-Badee	2	3	1	1	1	2	1.7	II	High
Al-Khazrajia	2	3	1	2	1	2	1.83	II	High
Al-Hammal	3	3	2	2	1	-	2.2	III	Moderate
Al-Ajeej	3	3	1	3	1	2	2.17	III	Moderate

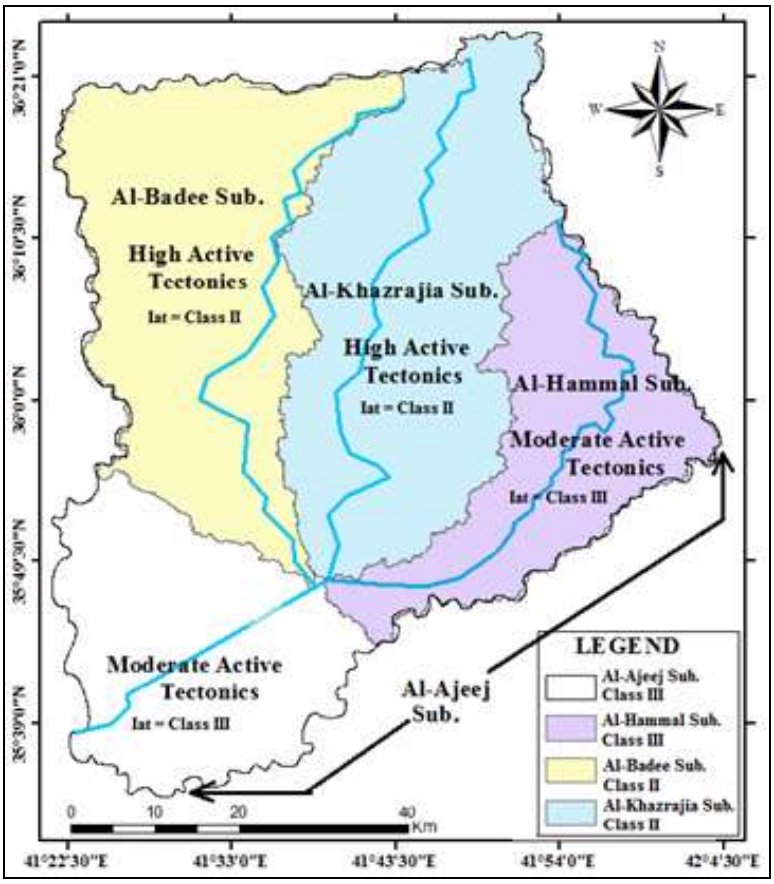

Fig.10: The relative active tectonics (***Iat***) affecting the studied sub-basins

DISCUSSION

The average of the six measured geomorphic indices (***SL, Bs, Af, Hi***, ***Vf*** and ***Smf***) was used to evaluate the distribution of relative tectonic activity. Each of the indices was divided into three classes. By averaging these six indices, we obtain one index that is a known relative active tectonic (***Iat***) (El-Hamdouni *et al*., 2008). The values of this index are divided into four classes to define the degree of active tectonics. The distribution of these four classes is shown in Fig. 8. In this figure, the low values of ***Iat*** that indicate High relative tectonic activity are in the north and western parts of the area in Al-Badee and Al-Khazrajia sub-basins, while the moderate values that indicate moderate relative tectonic activity are in the eastern and southern parts, which made the entire Al-Ajeej sub-basin affected by moderate active tectonics, although the Sinjar anticline and the buried subsurface structures.

The ***Sl***, ***Hi*** and ***Af,*** indices contribute in reducing the values of the relative tectonic activity (***Iat***) of Al Ajeej basin to the moderate class. An area of soft rocks with low ***Sl*** values (< 300) such the area under consideration can be indicative of Inactive tectonics, likewise **HC** of convex shape and the Hi low values, refer to equilibrium or the basin has reached the mature and old stage characterized by the lateral erosion.

Af index values are related to tectonic and non-tectonic controls. The non-tectonic is the lithology and rock fabric. The northern parts of the basin (Al-Badee and Al-Khazrajia sub-basins) are affected tectonically by the structural features which made the leftward and rightward tilting (***Vf*** > 50 and <50 respectively). These are very clear by the long tributaries to the right side of Al-Badee branch and the left side of the Al-Khazrajia branch. The other parts of the basin are affected by the low resistant lithology and the plain topography which made the basin relatively symmetric (***Vf*** close to 50). The deflection of the main stream trunks from S and SE to SW direction, as shown in the stream network map (Fig.2), are due to parallel subsurface structural features such as; faults, grabens or half grabens.

The low ***Sl*** values refer, the lithological control of the soft Quaternary sediments and low resistance of the underlying Injana clastics, that increases the ***Iat*** values to the Class III and consequently reduced the values of the relative tectonic activity (***Iat***) of the basin. ***Sl*** values less than 300 m represents those basins that are more affected by the streams erosive processes rather than active tectonics.

The elongated shapes of the three sub-basins (***Bs*** index results) reflect the tectonic effects of Sinjar anticline and subsurface structures on these sub-basins. Whereas, the entire Al-Ajeej basin shape is close to the circularity, indicating the equilibrium and attain the maturity or old stage. Also, both of the concave upward shapes of the ***HC*** and the ***Hi*** values, refer the basin attained the old stage. Only Al-Hammal sub-basin ***HC*** has the sigmoidal shape (S-shape) because it is initiated from low elevations (at 400m contour line).

All the ***Vf*** values, for up and midstream cross sections, refer to the high tectonic activity in the basin and its sub-basins in addition to the downstream cross sections indicate moderate active tectonics. These are due to the effects of the Sinjar anticline and the subsurface structural features. The calculated ***Smf*** values for the entire Al-Ajeej basin and its sub-basins are within class 2 of moderate active tectonics. That indicate the rate of uplift is reduced, and the erosional processes will carve a more irregular mountain front.

CONCLUSIONS

The class of "**High**" active tectonics characterizes the northern part of the basin, which is occupied by Al-Badee and Al-Khazrajia sub-basins. This is due to the existence of the Sinjar Anticline in the uppermost part of the basin and the subsurface extensional structures in the other parts, such as Tel-Hajar subsurface anticline in the western part. The flat topography and the soft and weak materials, which have filled more than 90% of the basin, reduced the tectonic activity of the entire Al-Ajeej basin to the **"Moderate**" (class III) according to ***Iat*** classification. This indicates that the erosional processes have overcome the tectonic activity and the initial development of alluvial plain. This study provides appropriate features for conducting morphometric analysis to understand the rate of erosion processes and tectonic activity in Wadi Al-Ajeej drainage basin.

REFERENCES

Ali, S.A., Ikbal, J., Ali, U. and Aldharab, H., 2017. "Measurement of watershed Geometry in the central part of Udaipur sector, Rajasthan using Remote Sensing and GIS" International Journal of Recent Scientific Research, Vol.8, Issue 11, p. 21786 – 21791.

Al-Taiee, T.M. and Rasheed, M.M., 2011. Hydro engineering Feasibility Study of Surface Runoff Water Harvesting in Al-Ajeej Basin, North West Iraq. Tikrit Journal of Eng. Sciences, Vol.18, No.1, p. 15 – 28.

Arian, M. and Aram, Z., 2014. Relative Tectonic Activity Classification in the Kermanshah Area, Western Iran. Solid Earth, Vol.5, p. 1277 – 1291. https://doi.org/10.5194/se-5-1277-2014

Azor, A., Keller, E.A. and Yeats, R.S., 2002. Geomorphic indicators of active fold growth: South Mountain-Oak Ridge anticline, Ventura basin, southern California. Geological Society of America Bulletin, Vol.114, No.6, p. 745 – 753.

Barman B.K., Koduri S.R. and Prasad N.S.R., 2017.Use of Geographic Information System in Hypsometric analysis of Chite Lui watershed, Aizawl district, Mizoram. Natural resources management for sustainability development and rural livelihoods (p. 1085 – 1096). Publisher: Today and Tomorrow's printers, New Delh.

Bhat F.A., Sana H., Iqbal M and Bhat I. M., 2013. Identification of geomorphic signatures of active tectonics in the West Lidder Watershed, Kashmir Himalayas: Using Remote Sensing and GIS. Inter. Jour. of Geomatics and Geosciences, Vol.4, No.1.

Bull, W.B., 1978. Geomorphic Tectonic Classes of the South Front of the San Gabriel Mountains, California. U.S. Geological Survey Contract Report, 14-08-001-G-394, Office of Earthquakes, Volcanoes and Engineering, Menlo Park, CA.

Bull, W.B., 2007. Tectonic geomorphology of mountains: a new approach to paleo-seismology. Blackwell, Malden. Binghamton, NY: State University of New York at Binghamton.

Bull, W.B. and McFadden, L., 1977. Tectonic geomorphology north and south of the Garlock Fault, California, Geomorphology in Arid regions, DO. Doehring, ed., Publications in Geomorphology, State University of New York at Bingamton, p. 115 – 138.

Cannon, P.J., 1976. Generation of explicit parameters for a quantitative geomorphic study of Mill Creek drainage basin. Oklahoma Geology Notes, Vol.36, No.1, p. 3 – 16.

El-Hamdouni, R., Irigaray, C., Fernandez, T., Chacon, J. and Keller, E.A. 2008. Assessment of relative active tectonics, southwest border of Sierra Nevad (southern Spain). Geomorphology: Vol.96, p.150 – 173.

Fouad S.F., 1997. Tectonic and Structural evolution of Anah region. Ph.D. thesis, University of Baghdad.

Fouad S.F., 1998. Tectonic and structural study of Tayarat Graben, West Iraq. GEOSURV, int. rep. no. 2459.

Fouad, S.F.A. and Nasir, W.A., 2009. Tectonic and structural evolution of Al-Jazira Area. In: Geology of the Iraqi Jazira Area. Iraqi Bull. Geol. Min., (ISSN-1811.4539), Special Issue, No.3, p. 33 – 48.

Fouad, S.F.A., 2012. Tectonic Map of Iraq, scale 1: 1000 000, 3rd edit. Publications of Iraq Geological Survey, Baghdad, Iraq.

Garg S.K., 1983. Geology-the science of the earth. Khanna Publishers, New Delhi.

Hack, J.T., 1957. Studies of longitudinal stream profiles in Virginia and Maryland. U.S. Geol. Surv. Prof. Paper, Vol.294, p. 45 – 97.

Hack, J.T., 1973. Stream Profile Analysis and Stream Gradient Index, U.S. Geological. Survey, Vol.1, p. 421 – 429.

Hack, J.T., 1982. Physiographic division and differential uplift in the piedmont and Blue Ridge, US Geol. Surv. Profess. Paper, Vol.1265, p. 1 – 49.

Hare, P.P.W. and Gardner, T.W., 1985. Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula Costa Rica. In M. Morisawa and J.T. Hack (Eds.). Tectonic Geomorphology proceedings of the 15th.

Huggett, R.J., 2007. Fundamentals of Geomorphology, 2nd edit. Routlege Taylor and Francis Group, London and New Yourk, 458pp.

Hurtez J.E., Sol, C. and Lucazeau F., 1999. Effects of drainage area on hypsometry from an analysis of small-scale drainage basins in Siwalik Hills (central Nepal). Earth surface processes and landforms, Vol.24, p. 799 – 808.

Keller, E.A. and Pinter, N., 1996. Active tectonics: Earthquakes, Uplift and Landscapes. Prentice Hall, New Jersey.

Keller, E.A. and Pinter, N., 2002. Active tectonics: Earthquakes, uplift and Landscape (second edition): Englewood Cliffs, New Jersey, Prentice Hall, 362pp.

Kirby, E. and Whipple, K.X., 2001. Quantifying differential rock-uplift rates via stream profile analysis. Geology, Vol.29, p. 415 – 418.

Ma'ala, K.A., 1976. Report on the Regional Geological Mapping of Hadhr Area. GEOSURV, int. rep. no. 742.

Ma'ala, K.A., 2009. Geomorpholgy of Al-Jazira Area. Iraqi Bull. Geol. Min. Special issue, No.3, p. 5 – 31.

Mosavi, E.J. and Arian M., 2015. Tectonic Geomorphology of Atrak River, NE Iran. Open Journal of Geology, Vol.5, p. 106 – 114. http://www.scirp.org/journal/ojg http://dx.doi.org/10.4236/ojg.2015.53010

Nasir W.A.A., 2001. Structural and tectonic evolution of graben system in north Arabian Plate. Unpub. M.Sc. Thesis. University of Baghdad, 85pp.

Pérez-Peña, J.V., Azor, A., Azañón, J.M. and Keller, E.A., 2010. Active tectonics in the Sierra Nevada (Betic Cordillera, SE Spain): Insights from geomorphic indexes and drainage pattern analysis. Geomorphology, Vol.119, p. 74 – 87.

Raj, R., Bandari, S., Maurya, D.M. and Chamyal, L.S., 2003. Geomorphic Indicators of Active Tectonics in the Karjan river basin, lower Narmada valley,Western India, Journal of Geological Society of India, Vol.62, p. 739 – 752.

Ramirez-Herrera, M.T., 1998. Geomorphic assessment of active tectonics in the Acambay graben, Mexican volcanic belt. Earth Surface Processes and Landforms, Vol.23, p. 317 – 332.

Ritter D.F., Kochel R.C., Miller J.R., 2002. Process geomorphology. McGraw Hill, Boston.

Sarp G., Gecen, V., Toprak and Duzgun, S., 2010. Morphotectonic Properties of Yenicaga Basin Area in Turkey. METU, Geodetic and Geographic Information. Technologies, Inonu Bulvari 06531 Ankara, Turkey, 5pp.

Singh, Q. Sarangi, A. and Sliarma, M.C., 2008. Hypsometric integral estimation methods and its relevance on erosion status of Northwestern Lesser Himalaya watershed, Water Res. Mgt. Vol.22, p. 1545 – 1560.

Sissakian, V.K. and Deikran, D.B., 1998. Neotectonic Map of Iraq, scale 1: 1000 000, GEOSURV, Baghdad, Iraq.

Sissakian, V.S., Abdul Jab'bar, M.F., Al-Ansari, N. and Knutsson, S., 2015. The Origin and Evolution of Wadi Al-Ajeej, Al-Jazira Vicinity, NW Iraq. Journal of Earth Sciences and Geotechnical Engineering, Vol.5, No.14, p. 69 – 83.

Strahler A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. Geologic Soc Am Bull, Vol.63, p. 1117 – 1141.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Trans. Am. Geophys. Union, Vol.38, p. 913 – 920.

Weissel, J.K., Pratson L.F. and Malinverno, A., 1994. The length-scaling properties of topography. J Geophys Res, Vol.99, p. 13997 – 14012.

Yacoub, S.Y., Othman, A.A. and Kadhim, T.H., 2012. Geomorphology of the Low Folded Zone. Iraqi Bull. Geol. Min., Special Issue, No.5, 2012: Geology of the Low Folded Zone, p. 7 – 37.

Yousif, L.D., 2019. Morphometric Analyses of Wadi Al-Ajeej Drainage Basin, Using GIS Technique. Iraqi Bull. Geol. Min., Vol.15, No.1, p 1 – 20.

About the Author

Mr. Luay Dawood Yousif graduated from Assiut University, Arab Republic of Egypt, in 1979 with B.Sc. in Geology. He got his M.Sc. degree from Baghdad University in 2005, in Rock Slope Engineering Geology. He joined Iraq Geological Survey in 1990, and was nominated as Senior Chief Geologist in 2004. His main field of interest is rock slope stability, rock and soil mechanics and construction raw materials. He has contributed to many of the Iraq Geological Survey projects, especially in engineering geology and geological mapping. He has many unpublished geological reports and ten (10) published papers.

e-mail: luayalobaidy1955@gmail.com; luaygeo@yahoo.com