HYPSONETRIC ANALYSIS OF AL-ADHAIM BASIN USING A NEW GIS-TECHNIQUE

¹Ahmed H. Al-Sulttani* and ²Ayad A. Beg

¹ Department of Environmental Planning, Faculty of Physical Planning, University of Kufa, Najaf, Iraq

² Department of Geography, College of Education, Mustansiriyah University, Baghdad, Iraq

Email: ahmedh.alsulttani@uokufa.edu.iq

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ABSTRACT

Al-Adhaim dam basin is extended across the boundaries of Salahuddin, Kirkuk, and Sulaymaniyah provinces in the northern part of Iraq, covering an area of 11831 km². The area is covered mainly in most upperparts by sedimentary rocks of the lower Eocene to Pliocene ages. The lower parts are occupied by sheet runoff deposits from the Quaternary age. The objectives of the current study are to carry out detailed measurements of hypsometric parameters to evaluate the degree of erosion conditions and to show the essential factors controlling the development of geomorphic stages in different parts of the basin. The analysis was carried out based on ASTER GDEM data using ArcGIS v10.6 hydrology toolbox and the morphometric toolbox and dividing the basin into fifteen sub-basins. The results show that the Al-Adhaim basin passes in the monadnock phase with a hypsometric integral of 19.02% and a highly concaved hypsometric curve. The sub-basins are classified into two groups of geomorphic stages, i.e., mature stage and Monadnock stage with hypsometric integral values between 18.4% and 34.6%. The results reveal the basin was controlled mainly by slopes, lineaments, Tertiary outcrops, Quaternary deposits, and hydrological soil groups B and D.

Keywords: Hypsometry; GIS applications; Morphometric toolbox; DEM; Al-Adhaim Dam

INTRODUCTION

The hypsometric analysis is a quantitative study of the drainage basin, and it reflects the geomorphic cycle and the manner of mass distribution in the basin. To understand the evolution and development of a landscape, the controlling factors such as weathering, deposition, erosion, and tectonic processes added to the fact that the lithology and hydrological behavior analysis are

required (Ahmed and Rao, 2016). Many methods and techniques have been used in computing the hypsometric parameters, and their accuracy depends on the analysis technique, source, and used data scale. The restriction of hypsometric measurement in the past due to the intensive computation requirement and limitation of measurement tools at that time and still, the hypsometric computation has been witnessed more interest with the use of planimeter as a more efficient tool for area measurement and visual assessment of the contours, while the advances in GIS techniques, make the hypsometric analysis worth more attention as a means for quantitative analysis of catchments (Dowling et al., 1998).

There are various studies were conducted to evaluate geomorphic stages, erosional conditions, and mass development of drainage basins. The importance of hypsometric analysis for the large basins is to study the overall slope of selected drainage basins (Langbein, 1947). The hypsometric properties are used to study small-scale basins of low order to evaluate the geomorphic cycle and determine the mass distribution within the basin from base to top (Miller, 1953; Schumm, 1956 and Strahler, 1952b). Hypsometric analysis of drainage basin is based on the hypsometric curve (HC) as a graphical representation of relative area situated above various altitudes on the abscissa, and relative altitude on the ordinate and hypsometric Integral (HI) calculated from the ratio of the area below HC to that of the rectangle delimited by the maximum values on the abscissa and ordinate (Strahler, 1952b; Strahler, 1957 and Zavoianu, 1985). The change in the shape of HC and values of HI is related to erosion processes, lithology, and structure (Moglen and Bras, 1995 and Willgoose and Hancock, 1998). The HI has been widely used in the interpretation of the stages of watersheds according to equilibrium and non-equilibrium phases of landscape because of uplift and denudation processes, and providing a measure of landmass volume distribution remaining beneath or above a basal reference plane (Ohmori, 1993; Singh et al., 2008; Strahler, 1952a; Vivoni et al., 2008 and Willgoose and Hancock, 1998). According to the HI values and HCs, the geomorphic cycle of erosion and the watershed are divided into three stages; Monadnock stage ($HI \leq 35\%$) refers to a phase represents isolated and erosion-resistant hills and mountains that rise above the general erosion level, which is called a peneplain (Vanderwaal and Ssegane, 2013), equilibrium, Mature stage ($35\% \leq HI \leq 60\%$) and non-equilibrium, Youth stage ($HI \geq 60\%$) mean the watershed is highly susceptible to more erosion (Strahler, 1952b).

The shape of HC changes from concave-convex to concave as the basin reaches the equilibrium mature stage (Soares and Riffel, 2006). HC and HI are strongly related to the erosional processes,

curvature, and morphology of landform (Cohen et al., 2008). HC is associated with i) the volume of the rock and soil mass and ii) the volume of eroded mass in a basin compared to the remaining mass (Hurtrez et al., 1999 and Singh et al., 2008). Khatun and Pal (2016) referred to the direct impact of basin topography on the shape of the hypsometric curve.

Although the effect of slopes on basin attributes, HC may be strongly influenced by the diverse geometry of the drainage network (Willgoose and Hancock, 1998). The runoff components are a function of the basin hypsometric form. The runoff amounts depend on the types of hydrologic soil groups described as group A, have low runoff and consist of mainly 90% gravel and 10% of clay, group B, when under wet conditions have a moderately low runoff, consist of 50 -90% of gravel, sand and the remaining from clay and silt or loam, group C, have moderately high runoff under wet conditions, consist of 20 - 40% of clay materials and less than 50% of sand, loam, and silt, and group D, water movement through such soil is restricted and make the soil have high runoff during wet conditions, consists of more than 40% of clay with less than 50% of sand and loam or silt materials (USGS, 2016). The use of SRTM data is essential in extracting the geomorphic features, terrain character, and analysis of hypsometric properties (Patel and Sarkar, 2010 and Sreedevi et al., 2009).

The current study aims to achieve the hypsometric analysis of Al-Adhaim dam sub-basins, using ASTER GDEM data, measuring the hypsometric parameters using the morphometric toolbox and analysis of the essential factors impact on development of the sub-basin's geomorphic stages, including geology, structure, drainage density, soil types, and slopes.

STUDY AREA

The Al-Adhaim dam's basin extended over three Iraqi governorates i.e., Salahuddin, Kirkuk, and Sulaymaniyah provinces cover an area of 11831.15 km². Geographically the basin is bounded by latitudes from 34° 30' to 35° 43'N and longitudes from 43° 45' to 45° 25'E (Fig. 1). The basin is entirely located within Iraqi land and represents a watershed for two rivers: Tuz Chi and Tauk Chi the main branches of Al-Adhaim River. Al-Adhaim meets the Tigris River south of Balad city region. The total annual precipitation in the study area is about 200 mm, and the mean annual temperature of about 28 °C. Al-Adhaim flow system can be classified as an irregular flow system that is controlled by precipitation and in the summer the river turns dry (Abbas et al., 2018).

Fig. 1. Location map of Al-Adhaim dam basin

GEOLOGIC AND STRUCTURAL SETTING

Geological formations are clipped from the geologic map (Sissakian, 1993). Geologic setting of the basin shows Tertiary formations mostly cover the eastern parts, Pila Spi and Gercus formations mainly consist of well-bedded bituminous chalky, crystalline limestone, mudstones, sandstones, sandy marls, and lenticels of gypsum are found towards the top of the upper Paleocene and lower Eocene ages (Fig. 2a). Fatha Formation is extended as narrow belts along the fault cliffs in the middle parts. It is comprised of anhydrite, gypsum, and salt interbedded with limestone and marl of middle Miocene age. Injana Formation consists of red to grey color silty marlstone or claystone, siltstones, and medium to coarse-grained sandstone of upper Miocene. Bai Hassan and mukdadia formations consist of pebbly sandstones, siltstone, claystone, and conglomerate of most upper Miocene–Pliocene ages (Buday, 1980; Rashid et al., 2016 and Sissakian, 1993). Quaternary deposits are mainly covered the western parts of the basin, predominately of sheet runoff deposits, gypsiferous soil and silty clayey sand (Al-Kubaisi et al., 2018; Jassim and Goff, 2006 and Sissakian, 1993). Several folds and lineaments are extended through the study area with a major axis in NW-SE direction, with recognized faults along the major tributaries of Al-Adhaim river (Buday and Jassim, 1987 and Marouf and Al-Kubaisi, 2005) (Fig. 2b). Dense joints are dominant in the eastern part of the basin, making the rocks more prone to erosion processes.

Fig. 2. a. Geological map (after Sissakian, 1993) b. Lineaments map

METHODOLOGY

To evaluate the geomorphic development, erosion processes in Al-Adhaim dam basin and its relations with calculated HI, many factors have been used for comparison which are (lineaments, geological formations and soils deposits HC, HI, DEM, Slopes, drainage network, basin and sub-basins are extracted and calculated from the Global Digital Elevation Model (ASTER GDEM) data. Lineaments have been extracted from Landsat 8 (USGS, 2016) using PCI-Geomatica.

Soil Types

The area is covered by various soil types ranged from deep to shallow phases, a reddish-brown soil of deep phase, badland, gullied land, lithosolic soil overlay the sandstones, gypsum, limestone rocks and brown soil of medium to shallow phase (Buringh, 1960 and Muhaimed et al., 2014) (Fig. 3a). Most of the soil types are developed in fluvial deposits and mixed weathering products of sandstones and gypsum rocks. The steeply sloped area is characterized by the presence of rough broken and stony land.

Topography

The topography of the area ranges in the elevations from 94 to 1840 meters above sea level. Gentle slopes are dominant in the western parts of the basin, whereas steep slopes characterize the eastern parts ranged from flat to very steep along the ridges area (Fig. 3b).

Fig. 3. a. Soil map, after (Buringh, 1960 and Muhaimed et al., 2014) b. Slopes map

GIS Technique and Analysis of Basin Hypsometry

Hypsometric calculation method

Although many tools and software are developed to do hypsometric analysis, the GIS software still has several drawbacks. One of the first extensions for hypsometric analysis execute with ArcView GIS and published on the ESRI website (Beg, 2008). For ArcGIS, hypsometry toolbox working under ArcGIS v.9.3 has been published which is required preparation of many layers, find main channel path flow, area gradient, stream gradient, maximum elevation and maximum flow length (Davis, 2010). The open software module was automated in System for Automated Geo-scientific Analyses (SAGA) has some limitations and problems (Sivakumar et al., 2011). Another tool for ArcGIS using Python language to calculate the topographic parameters, including area- elevation ratios have a drawback as well because it is required to draw HC (Gökgöz et al., 2016).

In this paper, a hypsometric analysis script has been used which is developed by the second author and published on ESRI website as a morphometric toolbox working under ArcGIS v.10.x. The analysis was carried out using a developed morphometric toolbox, as shown in Fig. 4. The

input layers are ASTER GDEM data (Fig. 5) and drainage network (Fig. 6a) to select the sub-basins outlets and delineate their watersheds. In the current study, fifteen sub-basins (Fig. 6b) are extracted from ASTER GDEM data using the ArcGIS v. 10.3-hydrology toolbox based on the flow directions; accumulation flows, drainage network and pour points of the outlets. The developed hypsometric analysis toolbox has been used as shown its windows in Fig. 7. DEM data and sub-basins boundaries layer are used as inputs to calculate HC and HI for Al-Adhaim sub-basins.

Fig. 4. Steps of the hypsometric analysis script

Fig. 5. ASTER- GDEM data

Fig. 6. a. Map of drainage networks b. Map of sub-basins

Fig. 7. Window of input layers and files used in the execution of hypsometric analysis script

The hypsometric analysis script is developed and used in this study to calculate the area under the curve (AUC) using the trapezoidal rule, Fig. 8 as follows (Kiusalaas, 2013):

$$I = [f(a) + f(b)] \frac{h}{2} \quad (1)$$

Where:

I = Area,

h = $\Delta x = b - a$, by substitution f(x) with f(h / H)

$$HI = \left(\sum_{i=1}^n \left(\left(\frac{h}{H} \right)_i + \left(\frac{h}{H} \right)_{i+1} \right) \times \frac{\left(\frac{a}{A} \right)_i - \left(\frac{a}{A} \right)_{i+1}}{2} \times 100 \right) \quad (2)$$

Where:

n = number of rows in hypsometric ratios table.

Fig. 8. Trapezoidal rules

Analysis the geomorphic stages by overlying the physical factors

The area of controlling factors of a geomorphic stage within each sub-basin was identified by the intersection and then followed by summarizing the results table based on sub-basin name by summing the area of each factor within the sub-basin; consequently, the areas are used to calculate the percentage of each factor within each sub-basin.

RESULTS AND DISCUSSION

The results of the hypsometric analysis of the entire basin are illustrated in area-elevation ratios in Table 1 and the main basin HC in Fig. 9. According to the HI of 19.03% and concave hypsometric curve, the basin has been passing in Monadnock geomorphic stage and fully stabilized watershed. The results of the spatial analysis of fifteen sub-basins are shown in HCs in Fig. 9 and HIs in Table 2. To focus light on the sub-basins, geomorphic stages and their controlling factor, area percentages of each factor are calculated as listed in Table 2 and illustrated spatially on maps in Fig. 10. From the achieved results; two groups of geomorphic stages are recognized, the first group including most of the sub-basins, sb6, sb15, sb1, sb13, sb3, sb2, sb7 sb12, sb10, and sb5 with HI values between 18.4% and 34.6%, obviously, the sub-basins are fully stabilized and passing in Monadnock geomorphic stage. The development of these sub-basins was affected mainly by dominant Tertiary age lithology, marl, limestone, gypsum, sandstone, siltstone, and claystone covering percentage between 9.9% at Sb12 to 100% at Sb2 and Sb6 with an average of 54.4%.

The sub-basins are located in the zone of moderate and strong to steep slopes, especially at Sb15, covered by 40.5%. Such relatively steep slopes lead to accelerating the weathering and erosion processes. Structurally, sub-basins are located in the folded zone with high lineament

density ranged from 0.19 to 0.46 km/kms with an average of 0.33 km/kms and rising of lineament density lead to increasing rock fragmentation and erosion processes. Hydrological soil group-A; recognized by gravelly soil with low runoff are dominant in sub-basins located at the downstream area of the Al-Adhaim dam basin, sb7, sb12, and sb1. In contrast, groups B, C, and D are more dominant in the other sub-basins. The second group of sub-basins includes sb8, sb9, sb11, sb14, and sb4, are passing in equilibrium and later maturity stage with HI range from 36.4% to 42.4%, indicating still some rock mass and soil materials are waiting for the weathering and erosion processes. Several factors are controlling the denudation process in these sub-basins including flat to gentle slope covering about 85 to 100% of the sub-basins area with an average of 92.9%, and these gentle slopes will reduce the erosion and transportation of water during surface runoff and lead to increasing drainage density in the area. The area covered by quaternary deposits of clastic materials and sheet runoff sediments covering 36.4 to 100% of the sub-basins area with an average of 70.6% and soil group-D mostly clayey soil with high runoff and low infiltration is more dominant in mature stage sub-basins. HC of sub-basins sb4 and sb14 shows erosion process at the upstream area and deposition at the downstream area. While HC of the most other sub-basins indicate, the eroded materials are mostly transported out of their catchments.

Table 1. Values of relative height (h/H), and relative area (a/A) ratios of Al-Adhaim basin

(h/H) ratio	(a/A) Ratio	(h/H) ratio	(a/A) Ratio	Minimum height(m) =94.0; Maximum height(m) =1840.0; elevation interval(m) =50; Total basin height(m) =1746.0; Total basin area (Km2) =11831.15; HI =19.02 (Monadnock stage)
0	1	0.48585	0.03969	
0.02858	0.97576	0.51443	0.02856	
0.05716	0.75391	0.54301	0.02116	
0.08574	0.62299	0.57159	0.01539	
0.11432	0.5491	0.60017	0.01123	
0.1429	0.48077	0.62875	0.0086	
0.17148	0.44408	0.65733	0.00649	
0.20006	0.40971	0.68591	0.0048	
0.22864	0.36882	0.71449	0.00348	
0.25722	0.32336	0.74307	0.00251	
0.2858	0.27383	0.77165	0.00186	
0.31438	0.22669	0.80023	0.00137	
0.34296	0.18325	0.82881	0.00096	
0.37154	0.14557	0.85739	0.00061	
0.40012	0.11633	0.88597	0.00028	
0.4287	0.08819	0.91455	0.00008	
0.45728	0.05906	0.94313	0.00002

Fig. 9. HC for sub-basins

Table 2. HI, geomorphic stages and controlling factors of the sub-basins

Sub-basin	Hypsometric integral (HI) (%)	Terrain slopes (%)			Geologic outcrops Age (%)		Lineaments density (LD) (km/kms)	Drainage density (Dd) (km/kms)	Hydrologic Soil group (%)				Geomorphic stage
		Flat to gentle (<8%)	Moderate (8-15) %	Strong to steep (>15%)	Tertiary	Quaternary			A	B	C	D	
Sb7	18.4	96.3	3.2	0.6	22.7	77.3	0.19	0.56	1.8	43.7	31.3	23.1	Monadnock
Sb2	23	60.3	27.5	12.3	100	0	0.35	0.5	0	67	8.9	24.1	
Sb3	24.2	67	22.5	10.6	96.7	3.3	0.41	0.53	0	79.1	2	18.9	
Sb13	24.3	76.4	23.2	0.4	49.6	50.4	0.36	0.56	0	10.6	18.3	71.1	
Sb1	26.5	97.1	2.4	0.5	46.4	53.6	0.45	0.53	23.6	15.8	37.4	23.3	
Sb15	27.8	36	23.6	40.5	74.4	25.7	0.35	0.4	0	0.1	99.9	0	
Sb6	28.7	86.8	10.6	2.7	100	0	0.46	0.51	0	19	0	81	
Sb5	30.7	99.4	0.6	0	22.1	77.9	0.23	0.6	0	13.7	5.3	81	
Sb10	32.1	99.6	0.4	0	22.1	77.9	0.26	0.58	0	4.4	9.5	86.1	
Sb12	34.6	97.8	2.1	0.1	9.7	90.3	0.27	0.54	15.4	3.6	45.5	35.5	
Avg.	27.03	81.7	11.6	6.8	54.4	45.6	0.33	0.53	4.1	25.7	25.8	44.4	
Sb4	36.4	84.9	13.1	2	63.6	36.4	0.22	0.52	0	61	1.5	37.5	Mature
Sb14	37.1	80.2	17.1	2.7	82.6	17.4	0.39	0.54	0	79.1	0	20.9	
Sb11	37.7	99.7	0.3	0	0.9	99.1	0.14	0.51	3	0	33.6	63.4	
Sb9	40.1	100	0	0	0	100	0.28	0.57	0	0	13.4	86.6	
Sb8	42.4	100	0	0	0	100	0.27	0.59	0	0	19	81	
Avg.	38.7	92.9	6.1	0.9	29.4	70.6	0.3	0.54	0.6	28.02	13.5	57.9	

Previous studies have mentioned that the morphometric characteristics of the studied area are based on traditional calculation methods and GIS techniques. A study was carried out on two sub-basins of Adhaim river basin, Tuz Chi and Sheikh Muhsin (Quri) sub-basins calculated the HI of the two sub-basins as 87% and 67%, respectively which means both are youth with slight tendency to mature in Sheikh Muhsin (Quri) sub-basin (Al Izzi, 2005) and another study was carried out on the morphometric characteristics of the basin and the effect of rainfall storm on the surface runoff and discharge of Adhaim river was calculated the HI of Al- Adhaim basin as youth basin with HI about 91.1% (Saloom, 2009). All the previous studies are not able to describe the erosion conditions and geomorphologic development stages in different parts of the Adhaim River basin. This

variation in the calculation of HI is due to human errors and a problem in the calculating area under the curve (AUC).

Fig. 10. Percentage distribution of essential controlling factors of sub basins

CONCLUSIONS

The most important conclusions based on developed hypsometric analysis GIS technique as the followings:

- 1- Al-Adhaim basin has been passing through Monadnock geomorphic stage with HI equal to 19.02%.
- 2- HC and HI results for sub-basins of Al-Adhaim basin are reached Monadnock geomorphic stage, and few of them are passing through the mature phase.
- 3- From intersected maps, sub-basins with Monadnock geomorphic stage show strong spatial relations with a high percentage of Tertiary formations area, high density of lineaments, high percentage of moderate slope and relatively high of steep slope, high percentage area of group-B of hydrological soil (Coarse soil).
- 4- From intersected maps, sub-basins with mature geomorphic stage show strong spatial relations with high percentage of Quaternary deposits area, low density of lineaments, high percentage of flat and gentle, high percentage area of group-D of hydrological soil (Fine soil), and related to high density which could due to sheet runoff because of flat and gentle slope.
- 5- In fact, the developed hypsometric analysis script of morphometric toolbox was proved as an efficient analysis GIS tool for facilitating the comparative analysis of sub-basins by exposing all the analyzed sub-basins to the same calculation measures and keeping the same accuracy degree of the results. The lithology, structure, slopes, and soil are the main factors controlling the denudation processes and development stages of Al-Adhaim dam sub-basins.

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