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Morphometric Analysis of Lake Langanu Watershed using Geographic Information System (GIS): in case of Lake Langeno Watershed, Oromia, Ethiopia

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Abstract

An understanding of watershed characteristics like areal, linear and relief aspect has paramount significance for watershed planning and management. An automatic extraction of these characteristics from digital elevation model is so effective and efficient. The main objective of this research work was Morphometric analysis of Lake Langanu watershed characteristics from Digital Elevation model using GIS. This research work employs an automatic extraction of hydrological characteristics using Geographical Information system. The results of finding show that the watershed has highly permeable soil type which absorbs the water passing over the soil. Drainage texture of the watershed is very coarse and the watershed is less affected by erosion. There is high runoff in the watershed due to large number of overland flow length. The shape of the watershed is elongated shape and experiences low peak flow over longer duration of time. Circulatory value of the watershed indicates that lake Langanu watershed is not under flood risk. Relief characteristics of the watershed indicate that most part of the watershed is characterized by gentle slope and the peak of south eastern part is characterized by steep slope.

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DEM (digital elevation model), GIS (Geographic Information system), Morphometric analysis, Watershed characteristics

Introduction

Background of the study

Watershed is defined as any surface area from which run-off (water) resulting from rainfall/snow melt is collected and drained through a common confluence outlet point. Hydrologically, watershed is an area from which the run-off drains through a particular point in the drainage system (Das, 2004). Watershed comprises surface water, groundwater and other natural resources, which are influenced by human activities. Quality and quantity of downstream has direct connection with the upstream activity of stream. The drainage basin is used as an ideal areal unit for Geo-morphometric analysis because it has inherent limited, convenient and usually

clearly defined and unambiguous topographic unit (Martinez *et al.*, 1998). Water is the principal motivating and integrating factor in hydrologic response studies. The concept of a watershed inherently integrates the upstream with the downstream through the flow of this central resource as part of the general hydrological cycle. A number of villages in a watershed often share the same stream as their water source. However, streamflow usually has high seasonal variability, and seasonal local water scarcity is a problem faced by many farmers in small watersheds (Jamtsho and Gyamtsho, 2003).

The natural region for water resources planning and development is often the river basin. River basins provide a geographic and functional context for many water-related purposes. Most waterprojects, particularly

reservoirs, can serve more than one of the basic purposes such as water supply, irrigation, hydroelectric energy, navigation, flood mitigation, recreation, pollution control, and wildlife conservation (Linsley *et al.*, 1992). Characterization of watershed is a necessary and important step in planning and management of a watershed. Defining the geographic boundaries of watersheds and sub-watersheds helps in gathering and evaluating data for watershed management (Rupesh Rathore *et al.*, 2018). The measurement and mathematical analysis of the configuration of the earth's surface and of the shape and dimensions of its landform provides the basis of the investigation of maps for a Geomorphological survey (Bates and Jackson, 1980). Information on topographic characteristics of the watershed helps in determining runoff and sedimentation to the outlet of the watershed.

Although watershed delineation at micro level (sub-watershed) is essential for effective planning and watershed management program, watershed characteristics such as size, slope, shape, drainage density, land use/land cover, geology and soils, and vegetation are important factors affecting various aspects of runoff (Rambabu Palaka and Jai Sankar, 2014). The Ziway–Shala lake basin system includes four present-day residual lakes, from north to south, Lake Ziway, Lake Langano, Lake Abijata, and Lake Shala respectively (Mekin *et al.*, 1976). Lake Langano watershed is one of the basin watersheds formed from the outlet point of drainage network at north eastern part of Langano Lake. The boundary of the watershed is delineated by rift valley lakes basin authority. However, analysis of the Lake Langano watershed characteristics in terms of linear, areal and relief aspect were not explicitly determined yet. Therefore, the main objective of this research work is morphometric analysis of Lake langano watershed using Geographic Information System as a tool. Specifically, this research work is intended to determine and quantify Areal, Linear and Relief aspects of Lake Langano watershed for better planning and management of Lake Langano watershed.

Materials and Methods

Description of study area

Lake Langano watershed is one of Zeway-shala lakes basin watersheds which is located at the northern part of great Ethiopian rift valley which covers an area of 2035 km square. Lake Langano watershed, falls between $7^{\circ} 10' 00''$ - $7^{\circ} 50' 00''$ latitude and $38^{\circ} 40' 00''$ - $39^{\circ} 10' 00''$

longitude (Fig. 1). The watershed stretches from the edges of the West Arsi Mountains in the southwestern and east show a mountains of Adami Tullu Jido Kombolcha in north eastern, rising over 4023 m above sea level (masl).

The north eastern part of the watershed is totally covered by Lake Langano. The entire of the watershed is covered by sparse acacia trees, and extensive cultivated field crop. The watershed inhabits millions of human and livestock population. The watershed does not have uniform climatic conditions. As the intensity, duration and frequency of rainfall events vary in the watershed throughout the year, both dry (locally named as Bega from January - May) and rainy (locally named as Kiremt from June- September) seasons are exchanged over the watershed.

Data source

To investigate watershed characteristics, both primary and secondary data were gathered from different sources. Primary data was collected in the field using Global Positioning System (GPS) to determine the watershed outlet point. In addition, GPS points gathered from the field was used as verification. Secondary data like DEM (Digital Elevation Model) was obtained from United States Geological Survey (USGS) freely.

Now a days, Shuttle Radar Topography Mission (SRTM) obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. The SRTM provides a number of DEM resolution outputs which is freely available in USGS websites. DEM (30 meter) was downloaded from USGS website (www.usgs.gov) for the study area. Five tiles (scene) DEM were needed to cover the whole area of the lake basin and all the scenes are downloaded from USGS website free of charges.

Data analysis

Digital Elevation Model (DEM) preprocessing

DEM data downloaded from USGS website needs preprocessing before being directly in use as an input data. Raw DEM data needs transformation of world reference system to local projection system. In this case, downloaded DEM was in Geographic Coordinate system and is projected to local Adindan datum. This helps to align the DEM together with other datasets in order to facilitate spatial analysis of input data. DEM was clipped

with the extent of the study area in order to reduce computational tasks for the whole area.

Digital Elevation (DEM) Analysis

Preprocessed DEM of the study area was analyzed using Hydrological tool in ArcGIS 10.6.1 software. DEM of the study area was first need be to filled in order to remove any sinks in the DEM.

Filling DEM sink provides sink free DEM which can be used as in input to derive flow direction of the study area. Flow direction tells as the direction of flow from every cell in the raster for hydrologic characteristics.

Flow accumulation was generated from flow direction to determine accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the DEM raster.

Linear aspects of the watershed such as stream order and stream link are derived from flow accumulation. The overall DEM processing for watershed characteristics analysis is depicted in Figure 2 which is adapted from ESRI.

Watershed morphometric analysis

Morphometric analysis is referred to the quantitative evaluation of characteristics of the earth surface and any landform unit. The composition of the stream system of a drainage basin is expressed quantitatively with stream order, drainage density, bifurcation ration and stream length ratio (Horton, 1945). There are basically three important aspects used for doing Morphometric analysis of a basin.

These are linear aspects, Areal aspects and Relief aspects. Linear aspects give the information about one dimensional parameter like: Stream Order, Stream Number and Bifurcation Ratio. Areal aspects deal with two dimensional parameters like: Drainage Density, Stream Length, Stream Length Ratio, Drainage Texture, Stream Frequency, Circularity Ratio and Form Factor.

Relief Aspects deals with three dimensional parameters like: Relief, Relief Ratio, Slope and Gradient Ratio. For Lake Langanu watershed, three types of Morphometric analysis were selected. The mathematical formulae for Morphometric parameter analysis were adapted from different literatures (Table 1).

Results and Discussions

Linear aspect

Stream order

Stream ordering is a method of assigning a numeric order to links in a stream network. This order is a method for identifying and classifying types of streams based on their numbers of tributaries. The stream ordering systems has first advocated by Horton (1945), but Strahler (1952) has proposed this ordering system with some modifications. For this research Strahler (1952) method was used for ordering streams along the lake langano watershed. In the Strahler method, all links without any tributaries are assigned an order of 1 and are referred to as first order. The intersection of two first-order links will create a second-order link and also intersection of first-order with second order results second order. The intersection of two second-order links will create a third-order link. Five types of stream order (First order, second order, third order, fourth and fifth order) was generated for Lake langano watershed.

Basin length (Lb)

Schumm (1956) defined the basin length as the longest dimension of the basin parallel to the principal drainage line. Gregory and Walling (1973) defined the basin length as the longest in the basin in which end being the mouth. Basin length can be measured in ArcGIS with distance measuring tool. Length of Lake Langanu watershed was measured in ArcMap using distance measuring tool. The longest measured Length of the watershed is 65 km.

Stream length (L)

The total sum length of each stream order is calculated as summation of each individual segment in that order. Mean stream length of each order is calculated as the total sum of stream length in each order divided by the number of streams in that order. The following table 2 depicts stream length of each order and mean stream length of each stream order for Langanu lake watershed.

Bifurcation ratio (Rb)

The bifurcation ratio is the ratio of the number of the stream segments of given order to the number of streams in the next higher order. Strahler (1957) demonstrated that bifurcation shows a small range

of variation for different regions or for different environment except where the powerful geological control dominates. The bifurcation ratio is dimension less property and generally ranges from 3.0 to 5.0. The lower values of bifurcation ratio are characteristics of the watersheds, which have suffered less structural disturbances (Strahler1964) and the drainage pattern has not been distorted because of the structural disturbances(Nag 1998). In lake langano watershed, the lower values of bifurcation ratio indicate strong structural control on the drainage pattern, while the higher values indicative of watershed that are affected by structural disturbances (Table 3).

Areal aspect

Drainage Density (Dd)

Drainage density (Dd) shows the landscape dissection, runoff potential, infiltration capacity of the land, climatic conditions and vegetation cover of the basin. High drainage density is the resultant of weak or impermeable subsurface material, sparse vegetation and mountainous relief. Low drainage density leads to coarse drainage texture while high drainage density leads to fine drainage texture (Strahler, 1964).

$Dd = L/A$ Where L= Total length of stream, A= Area of the basin

$$Dd = \frac{952.15}{2035} = 0.47$$

The Line Density tool in ArcMap calculates the density of linear features in the neighborhood of each output raster cell. Drainage density is a better quantitative expression to the dissection and analysis of landforms. Drainage density of Lake Langano watershed was generated from stream channel using stream length field value as an input. According to (Nag, 1998), drainage density is an indicator of basin permeability. The results of drainage density for Lake Langano watershed was 0.47 which shows very low and this reveal that the permeability of the soil is very high.

Stream frequency (Fs)

Stream frequency (Fs), is expressed as the total number of stream segments of all orders per unit area. Generally, high stream frequency is related to impermeable sub-surface material, sparse vegetation, high relief conditions

and low infiltration capacity (Horton, 1962). The total stream number of Lake langano watershed resulted from five stream order is 162 (Table 4). Subsequently, the total area of the watershed resulted from ArcMap area calculation is 2,035 square kilometer. Stream frequency of Lake Langano watershed is calculated in the following manner.

$Fs = N/A$ Where N= Total number of streams, A= Area of the basin

$$Fs = \frac{162}{2035} = 0.079$$

Drainage texture (Dt)

Horton (1945) defined drainage texture is the total number of stream segments of all order in a basin per perimeter of the basin. More is the drainage texture more will be dissection and leads more erosion. Drainage texture is one of the important concepts of geomorphology which means that the relative spacing of drainage lines. Drainage texture is on the underlying lithology, infiltration capacity and relief aspect of the terrain. (Smith, 1950) has classified drainage texture into five different textures i.e., very coarse (<2), coarse (2 to 4), moderate (4 to 6), fine (6 to 8) and very fine (>8). Drainage texture of the watershed is calculated as total stream number of all order which is 162 divided by perimeter of the watershed (216 km). Accordingly, the drainage texture of the watershed is equal to 0.75 which is very coarse according to the definition of (Smith, 1950).

$Dt = N/P$ Where N= Total number of streams, P= Perimeter of the basin

$$Dt = \frac{162}{216} = 0.75$$

Length of overland flow (Lo)

According to (Horton 1945), length of overland flow is determined as half the average distance between stream channels of each order. Length of overland flow is one of the most important variables affecting hydrologic and physiographic development of drainage basin. In Lake Langano watershed, the mean of the stream length is 5.87. Horton (1945) realizes that length of overland flow determines the surface runoff characteristics. This means

that higher length of overland flow shows high surface runoff. So, Lake Langanu watershed length overland flow is 2.935 and it shows higher surface runoff in the watershed. Length of overland flow (Lo) for Lake Langanu watershed is calculated in the following manner.

$$Lo = \frac{1}{2}(\bar{L})$$

; Where, Lo = length of overland flow, L bar = Mean of stream length.

$$Lo = 1/2 (5.87) = 2.935 \text{ KM}$$

Form factor (Ff)

Form factor is defined as the ratio of the basin area to the square of the basin length. The form factor value should be always less than 0.7854 (the value corresponding to a perfectly circular basin). The smaller the value of the form factor, the more elongated will be the basin. Basins with high form factors experience larger peak flows of shorter duration, whereas elongated basins with low form factors experience lower peak flows of longer duration. Calculated area and measured length of the watershed is 2,035 square kilometer and 65km respectively. Computed Form factor of the watershed is 0.48. The result of form factor shows that the watershed is elongated shape starting from initial point of the stream to the outlet point. So, Lake Langanu watershed experiences low peak flow over longer duration of time.

$$Ff = \frac{A}{(Lb)^2}$$

Where, A = area of the basin, Lb = length of the basin

$$Ff = \frac{2035km^2}{(65km)^2} = 0.48$$

Circulatory ratio (Cr)

The circulatory ratio is originally defined by Miller (1953), as the ratio of the area of the basin to the area of the circle having same circumference as the basin perimeter. Circulatory ratio is helpful for assessment of flood hazard. Higher the circulatory value, higher is the flood hazard at the peak time at the outlet point. Circulatory ratio of Lake Langanu watershed is 0.54 which is very low compared to the shape of the watershed. Lower circulatory ratio of the watershed

shows that the watershed is not as much as under flood risk.

$$Cr = \frac{4\pi A}{P^2}$$

Where A = Area of the basin, π = 3.14, P = perimeter of the basin

$$Cr = \frac{4*3.14(2035)}{(216*216)} = 0.54$$

Elongation ratio (Er)

Schumm’s (1956) used an elongation ratio as the ratio of diameter of a circle of the same area as the basin to the maximum basin length. The value of elongation ratio varies from 0 (in highly elongated shape) to unity i.e. 1.0 (in the circular shape). Thus, higher the value of elongation ratio more circular shape of the basin and vice-versa. Values close to 1.0 are typical of regions of very low relief, whereas that of 0.6 to 0.8 are usually associated with high relief and steep ground slope (Strahler, 1964). Computed elongation ratio value for Lake Langanu watershed is 0.78 which lies between the ranges of 0.6 to 0.8. According to the value of elongation ratio, Lake Langanu watershed is characterized by high relief and steep slope. High relief and steep slope part are located at the south eastern part of the watershed. Where as the mouth of the watershed is characterized by gentle slope following, flat area of the watershed.

$$Er = \frac{2\sqrt{\frac{A}{\pi}}}{Lb}$$

Where A = area of the basin, Lb = length of the basin

$$Er = \frac{2\sqrt{\frac{2035}{3.14}}}{65} = 0.78$$

Relief aspect

Elevation

Elevation is defined as land surface height relative to surface of mean sea level. Digital elevation model data describes continues elevation of the watershed. The highest and lowest elevation of Lake Langanu watershed is 4023 m and 1551 m respectively. South eastern peak of the watershed is characterized by highest elevation and north eastern part of the entire watershed is characterized by low elevation (Fig. 3–6).

Table.1 Formulae for calculation of different watershed parameters

No.	Morphometric parameter	Formula	Reference
1	Stream order	Hierarchal rank	Strahler (1952)
2	Stream Length	Length of each N order	Schumn (1956)
3	Bifurcation ratio	$R_b = N/N+1$	Strahler (1957)
4	Drainage density	$D_d = \sum L/A$	Strahler (1964)
5	Stream frequency	$F_s = \sum N/A$	Horton (1932)
6	Drainage texture	$D_t = N1/P$	Horton (1945)
7	Form factor	$F_f = A/(L_b)^2$	Horton (1932)
8	Circulatory Ratio	$C_r = 4\pi A/(P)^2$	Miller (1953)
9	Elongation ratio	$E_r = 2\sqrt{(A/\pi)}/L_b$	Strahler (1964)
10	Length of overland flow	$L_o = \frac{1}{2}(\bar{L})$	Horton (1945)
12	Elevation	Elevation number in meter	
13	Slope	(rise/run) x 100	

N=stream number, L=stream length, A=area of watershed, P=perimeter of watershed, L_b=length of the basin, \bar{L} =mean of stream length, H=maximum elevation, h=minimum elevation

Table.1 Stream length and mean stream length of each order

Stream Order	Stream number	Sum length of each order
First Order	84	478.24
Second Order	48	324.59
Third Order	14	110.05
Fourth Order	8	30.96
Fifth Order	8	8.31
		Total sum: - 952.15
		Mean: - 5.87

Table.2 Bifurcation ratio

Stream Order	Stream number	Bifurcation ratio (R _b)
First Order	84	-
Second Order	48	1.75
Third Order	14	3.42
Fourth Order	8	1.75
Fifth Order	8	1

Table.3 Quantitative results of Lake Langano watershed characteristics

No.	Morphometric parameter	Results
1	Stream order	Five orders
2	Stream Length	952.15 (total length)
3	Bifurcation ratio	Ranges from 1-3.5
4	Drainage density	0.47
5	Stream frequency	0.079
6	Drainage texture	0.75
7	Form factor	0.48
8	Circulatory Ratio	0.54
9	Elongation ratio	0.78
10	Length of overland flow	2.935 km
11	Elevation	Ranges from 1551-4023 m
13	Slope	Ranges from 0-300 percent

Figure.1 Study area

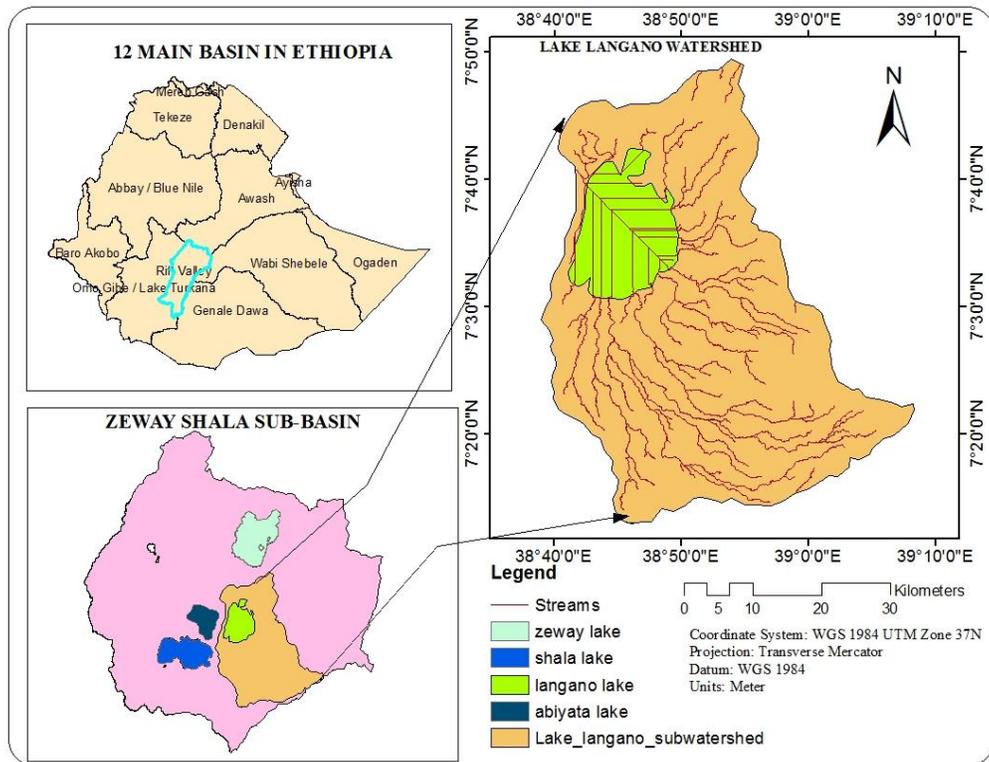


Figure.2 Flow chart that depicts Hydrological analysis of Lake langano watershed [source: ESRI]

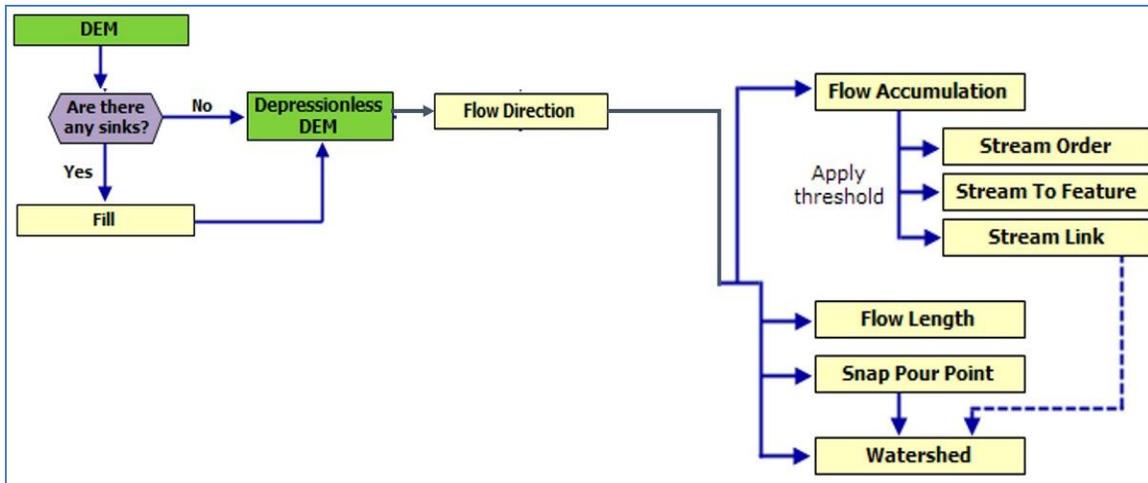


Figure.3 Strahler stream ordering

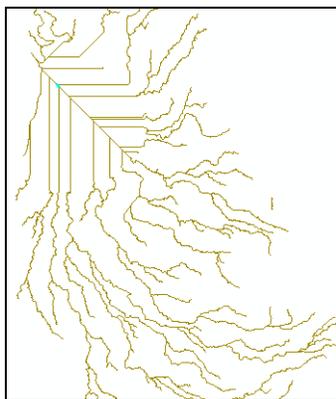
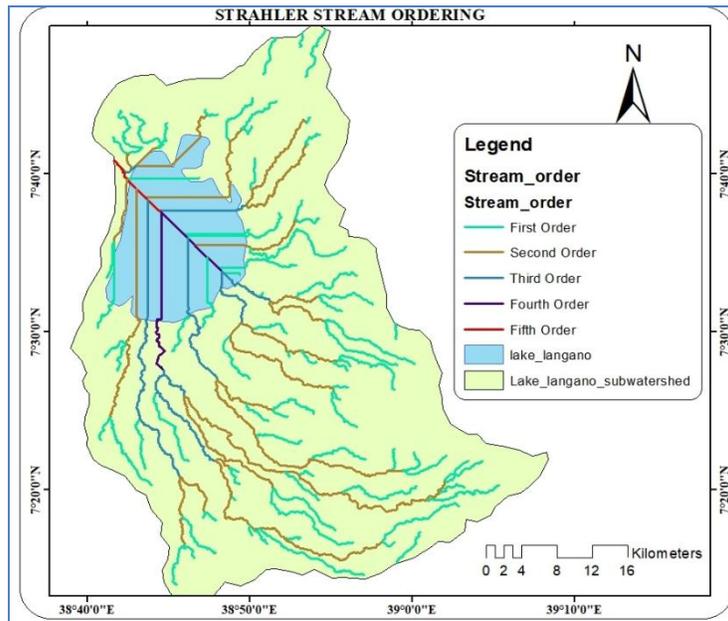


Figure.4 Drainage density

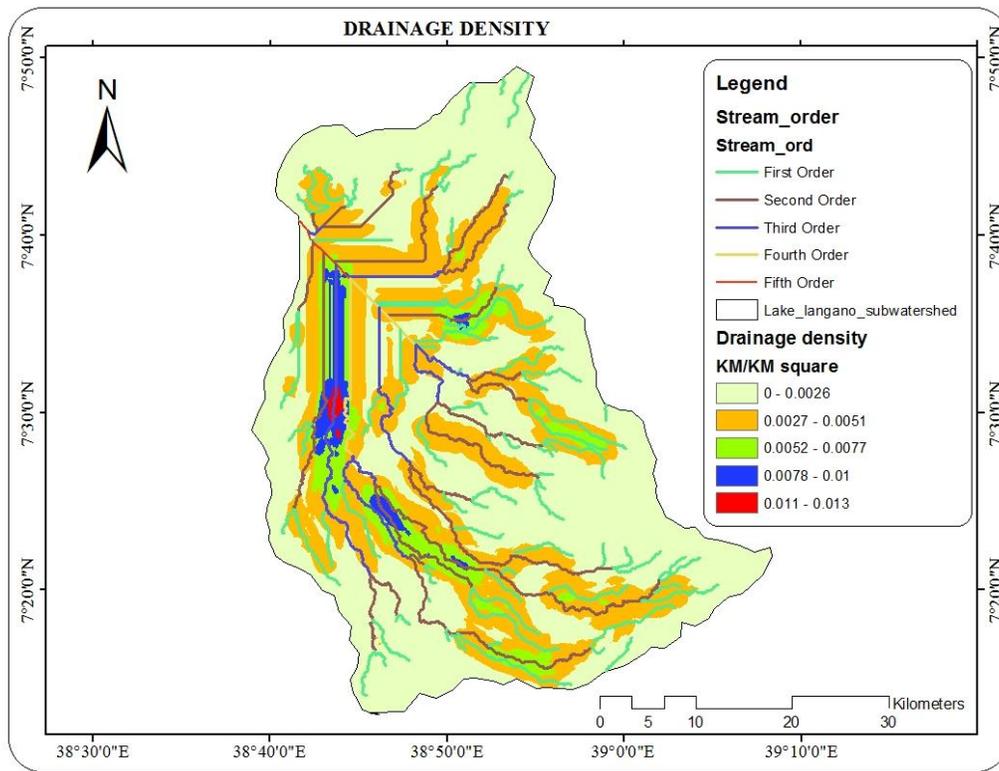


Figure.5 Elevation

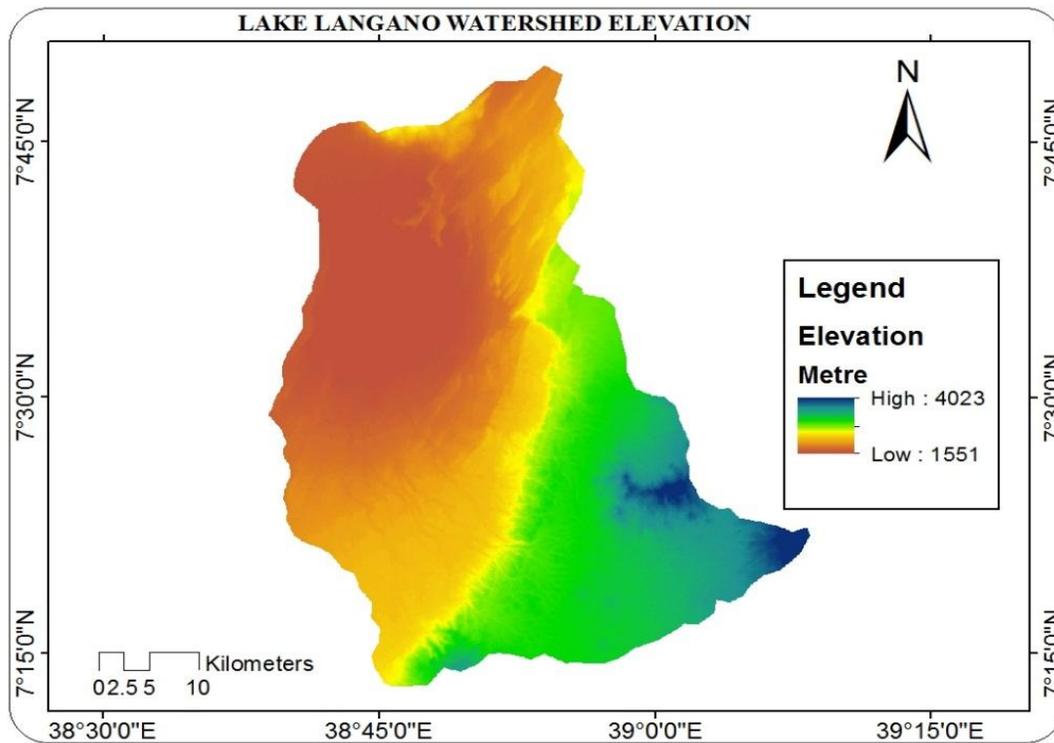
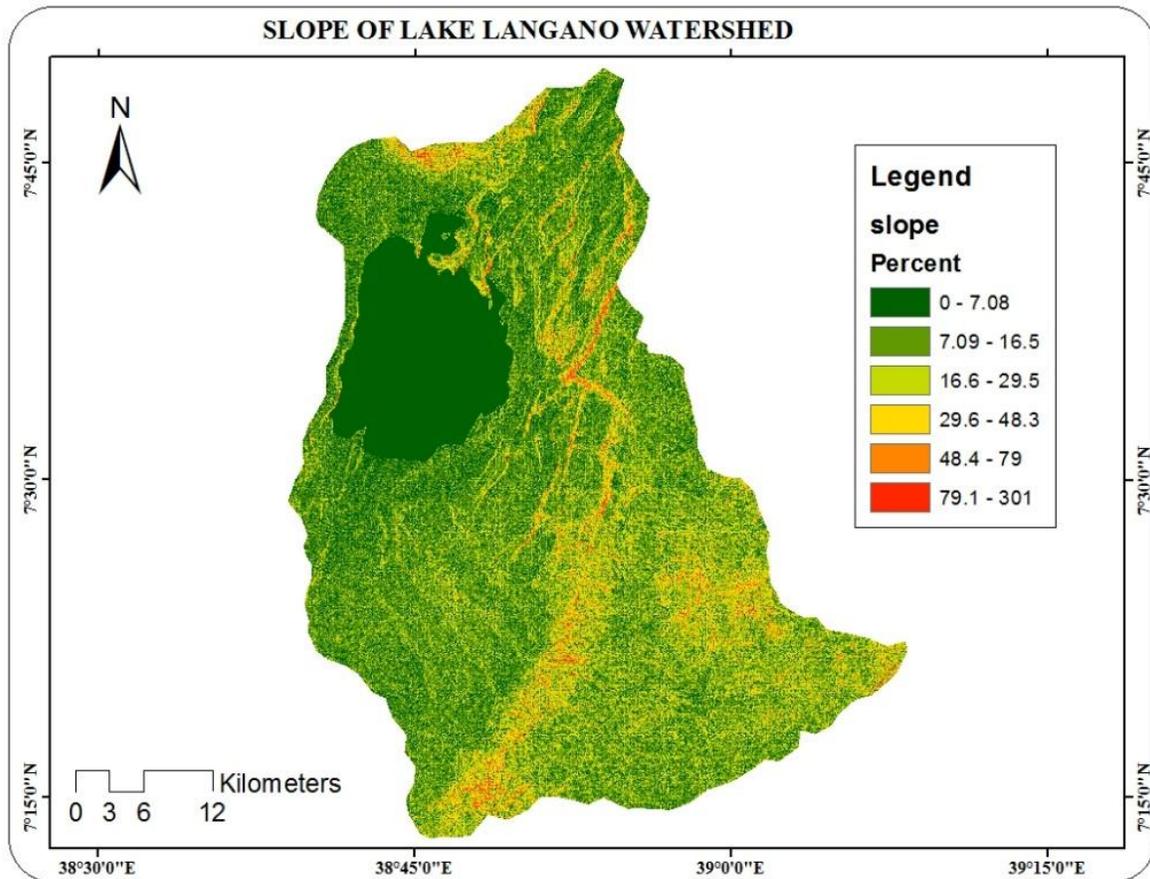


Figure.6 Slope



Slope

Slope describes the incline or steepness of a surface. Slope can be measured in degrees from horizontal (0–90), or percent slope (which is the rise divided by the run, multiplied by 100). Slope of Lake Langanu watershed is calculated using percent in ArcGIS 10.6.1 software.

In conclusion, the hydrologic modeling tools in the ArcGIS Spatial Analyst extension toolbox provide methods for describing the physical components of a surface. The hydrologic tools allow as identifying sinks, determining flow direction, calculating flow accumulation, delineating watersheds, and creating stream networks. Besides hydrological modeling of a given watershed, quantitative assessment of watershed characteristics is an important function. In this study, quantitative Morphometric analysis of Lake Langanu watershed was performed. Three aspects of Morphometric analysis were examined to explore Lake Langanu watershed characteristics. Lake Langanu

watershed has five stream orders with predefined threshold value of 1000 pixels. Bifurcation ratio of the stream orders shows that second, fourth and fifth orders have strong structural control on drainage pattern. Whereas, third order have weak structural control and affected by structural disturbance. The watershed has highly permeable soil type which absorbs the water passing over the soil. Drainage texture of the watershed is very coarse and the watershed is less affected by erosion. Drainage density is a better quantitative expression to the dissection and analysis of landforms. Drainage density of Lake Langanu watershed was generated from stream channel using stream length field value as an input. The results of drainage density for Lake Langanu watershed was 0.47 which shows very low and this reveal that the permeability of the soil is very high. There is high runoff in the watershed due to large number of overland flow length. The shape of the watershed is elongated shape and experiences low peak flow over longer duration of time. Circulatory value of the watershed indicates that lake Langanu watershed is not under flood risk. Relief characteristics of the

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