Quantitative evaluation of watershed attributes for water resources management in the Rift Valley Lakes Basin, Ethiopia: a case from Tikur Wuha river watershed

Rediet Girma1 · Tesfalem Abraham2 · Alemayehu Muluneh3

Received: 25 February 2020 / Accepted: 15 July 2020 / Published online: 31 July 2020 © The Author(s) 2020

Abstract
Characterization of watershed hydrological process is vital for sustainable water resource management. The principal goal of this study was to investigate the inference of drainage attributes on basic hydrological processes using spatial-based morphometric analysis on Tikur Wuha river watershed. The result obtained indicated that the area was characterized with fifth-order stream. Drainage area with higher stream order has lower infiltration capacity, and the shorter stream lengths were associated with the steepness of the area which affects water flow. Based on $N_u$ value, sub-watersheds were categorized in the active erosion stage (SW7) and matured topography development (SW6). The interpretation from watershed geometry identified circular areas most susceptible to rapid hydrological response (SW11). Hydrological process and underlying materials are mainly correlated with the drainage texture parameter, and the lower the values indicated less rocky terrain and very high infiltration capacity which contributes toward less erosion (SW11). Relief parameters such as $R_r$ value indicate the rate of stream flow and are well used in sediment yield estimation. The findings of this investigation will provide core information for water resource planning and further studies like identification of groundwater potential zones; flood risk assessment; erosion-prone area prioritization; and to select suitable sites for the construction of water harvesting structures.

Keywords Water resource · Hydrology · Morphometric analysis · Tikur Wuha

Introduction
Morphometric analysis of a drainage basin is a quantitative investigation of a basin attributes, and it is an important aspect to know the linear, aerial and relief character of a basin (Strahler 1964; Ayele et al. 2017; Tesfaye and Wondimu 2014). Mathematical analysis of drainage basin features provides useful inputs in order to characterize and understand various hydrological processes for planning and management (Farrukh et al. 2013; Tesfaye and Wondimu 2014; Yangchan et al. 2015). Since long ago, Horton (1945) and Strahler (1964) tried to indicate the association between morphometric parameters and basin hydrology. As many scholars said, the implementation of watershed management is fundamental to achieve sustainable uses of land and water resources to mitigate the increasing demand (Javed et al. 2009; Rai et al. 2017, 2018; Prakash et al. 2019).

Morphometric characterization assists decision makers in watershed management as it is considered to be the most acceptable method for good watershed management (Geena and Ballukraya 2011; Markose et al. 2014). Morphometric method has been used as a tool to know the area–height correlation and its implication on watershed hydrology for water resource planning (Kanth 2012; Bharadwaj et al. 2014). With the advent of remote sensing (RS) and geospatial information technology (GIS), as several studies confirmed, GIS-based morphometric analysis is most effective,
time saving and accurate technique for watershed characterization, planning and management (Benukantha et al. 2019).

The Rift Valley Lakes Basin of Ethiopia has undergone a major land use change in the past, and such alterations remain vivid nowadays too, affecting the hydrology and ecology of the basin (WWDSE 2001). The inflow of runoff with heavy silt to Lake Hawassa causes rapid storage loss and an increase in the level of the lake (Mulugeta 2013; World Meteorological Organization 2003; Halcrow Group Limited and Generation Integrated Rural Development (GIRD) Consultants 2008; Yacob 2010). Tikur Wuha river is perennial river that flows to Lake Hawassa, and its drainage area covers approximately half of Lake Hawassa watershed and has been deforested over the past few decades (Yacob 2010; Wolka et al. 2014) causing hydrological imbalance on the lake. The main objective of this study was to implement GIS-assisted morphometric characterization on Tikur Wuha river watershed to reveal its impact on basic hydrological process.

Materials and methods

Study area description

Tikur Wuha river is the major tributary of Lake Hawassa, Ethiopia, draining from the eastern part of the lake watershed (Fig. 1). Tikur Wuha river watershed is found in the northeast shore of Lake Hawassa geographic location of 6048’00”–7010’00”N latitude and 38°26’30”–38°43’00”E longitude. Its altitude ranges between 1643 m and 2976 m above mean sea level. Agroecologically, the study area was classified into midland and highland. Land use in the watershed is dominated by agriculture/intensive cultivation (Yacob 2010).

Datasets used

Drainage aspects of Tikur Wuha river watershed were mathematically measured using hydrological tools in ArcGIS 10.7.1 setup. To carry out the analysis, digital elevation model (DEM) from https://earthexplorer.usgs.gov/ with 20 m by 20 m resolution was acquired as a data source. Prior to morphometric analysis, delineation of watershed boundary and digitization of all existing stream including its tributaries were done digitally in ArcGIS package (Kotei et al. 2015). Sink fill and flow direction was computed to understand which way the water is flowing by comparing each cell with its neighboring using the eight-direction pour-point method (ESRI 2011). The accumulated number of cells that are draining to any particular cell was also identified using the flow direction grid to define the stream network and determine where streams turn into river. Then, watershed subdivision was carried out after stream segmentation (Gajul et al. 2016; Panhalkar et al. 2012). In this study, the mathematical expression (Table 1) of morphometric parameters assembled into linear aspect, watershed geometry,
drainage texture and relief parameters was adopted from different sources. Further, the geological map of the study area was also used to correlate the underlying conditions with the morphometric parameters.

### Analysis of morphometric attributes

#### Interrelation between parameters

To understand how the different morphometric parameters interact and influence each other, the relationship between variables was tested using graphical regression equation and tabular correlation matrix (Ali and Hassan, 2018).

### Table 1 Adopted mathematical equations to compute the morphometric parameters

| Parameters          | Name                          | Given equation                                                                 | References |
|---------------------|-------------------------------|-------------------------------------------------------------------------------|------------|
| Linear aspect       | Stream order (u)              | Hierarchical rank                                                            | Strahler (1952) |
|                     | Stream number (Nu)            | Nu = N1 + N2 + ⋯ + Nn, where Nu = N of segments of order ‘u’                  | Horton (1945) |
|                     | Stream length (Lu)            | Lu = L1 + L2 + ⋯ + Ln, where Lu = total stream length of order ‘u’ (km)       | Horton (1945) |
|                     | Mean stream length (Lum)      | Lum = Lu / Nu, where Lum = mean stream length of order ‘u’                     | Horton (1945) |
|                     | Stream length ratio (Lur)     | Lur = Lum / Lum−1                                                             | Horton (1945) |
|                     | Bifurcation ratio (Rb)        | Rb = Nu / N+1, where N+1 = N of segments of next higher order                 | Strahler (1964) |
|                     | Mean bifurcation ratio (Rbm)  | Rbm = Average of bifurcation ratio of all orders                             | Strahler (1964) |
|                     | Rho coefficient (p)           | p = Lur / Rb                                                                  | Horton (1945) |
| Geometric features  | Basin length (Lb)             | Length of the basin (km) obtained from ArcGIS                                | Horton (1945) |
|                     | Area of the basin (A)         | Plan area obtained from ArcMap (km²)                                          | Horton (1945) |
|                     | Basin Perimeter (P)           | Perimeter (km) obtained from ArcMap                                           | Horton (1945) |
|                     | Shape factor ratio (Bf)       | Bf = L² / A                                                                  | Horton (1945) |
|                     | Form factor ratio (Fr)        | Fr = N² / L²                                                                | Horton (1932) |
|                     | Elongation ratio (Re)         | Re = 2√(A/π)/Lb                                                             | Schumm (1956) |
|                     | Circularity ratio (Rc)        | Rc = 4πA / P²                                                                | Strahler (1964) |
|                     | Fitness ratio (Ff)            | Ff = C/ P                                                                  | Melton, 1957 |
|                     | Compactness coefficient (Cc)   | Cc = 0.2824 * p / √A                                                         | Gravelius (1914) |
| Drainage texture    | Drainage density (Dd)         | Dd = L / A                                                                  | Horton (1932) |
|                     | Length of overland flow (Lg)  | Lg = 1 / 2Dd                                                                 | Horton (1945) |
|                     | Stream frequency (Fs)         | Fs = H / HLb − Lb                                                            | Horton (1932) |
|                     | Drainage intensity (Id)       | Id = Fs / Dd                                                                 | Faniran (1968) |
|                     | Texture ratio (Dt)            | Dt = N / P                                                                  | Horton (1945) |
|                     | Infiltration number (Ii)      | Ii = D × Fs                                                                  | Praveen et al. (2018) |
|                     | Constant of channel maintenance (C) | C = 1 / D                    | Schumm (1956) |
| Relief aspect       | Basin (relative) relief (H)   | H = Z−z, where Z = maximum basin highest and z = minimum height (m)          | Strahler (1952) |
|                     | Relief ratio (Rr)             | Rr = H / Lb                                                                 | Schumm (1956) |
|                     | Relative relief ratio (Rrp)   | Rrp = H * 100 / P                                                           | Melton (1958) |
|                     | Ruggedness number (Rn)        | Rn = D * 1/100                                                              | Patton and Baker (1976) |
|                     | Dissection index (Dis)        | Dis = H / Hmax                                                              | Singh and Dubey (1994) |
|                     | Hypsometric curve             | Plot of relative area with relative altitude                                 | Strahler (1952) |
Results and discussion

The hydrological response of a catchment was largely controlled by its morphometric parameters (Diakakis 2010). Analyzing morphometric variables of Tikur Wuha river watershed plays an important role to understand various hydrological processes. The result obtained from the morphometric analysis and its implication on the hydrology of the river watershed was discussed henceforward:

Linear aspect

Stream order ($u$)

SW5 specifically and the study watershed in general accounted for fifth-order stream (Fig. 2) with dendritic type of drainage pattern. It is considered as the trunk stream through which all discharge of water and sediment passes (Strahler 1957). However, SW4, SW5, SW7, SW12 and SW13 were assigned as fourth order and SW1 was the only one assigned as second order. The remaining eight SWs were categorized as third-order stream hierarchic. Stream order is inversely correlated with infiltration capacity; the higher the $u$ value, the lesser in terms of permeability and infiltration (Gajbhiye et al. 2015). Hence from water resource management aspect, construction of water harvesting structures and the implementation of artificial recharge should be encouraged based on the biophysical condition.

Stream number ($N_u$)

The $N_u$ per each SW is tabulated in Table 2, 13.5% of the total $N_u$ was situated in SW7, and SW6 accounts the smallest of all, that is, 1.8%. Across the watershed, 273 $N_u$ were counted. In one way or the other, $N_u$ indicates the erosional status and development stage of a given watershed (Gutema et al. 2017). Hence, relatively large $N_u$ as in the case of SW7 indicates the topography is still undergoing erosion and the lesser the value (SW6) implies matured topography. It is

![Fig. 2 SW with drainage network (left); flow direction and flow accumulation map (right)]
| SW | Stream number (N_u) | Stream length, L_u (km) | Mean stream length, L_um (km) | Stream length ratio (L_r) | Mean Lur (L_rum) |
|----|---------------------|------------------------|-------------------------------|--------------------------|-----------------|
|    | I | II | III | IV | V | Total | I | II | III | IV | V | Total | I | II | III | IV | V | Total | I/I | III/II | IV/III | V/IV |
| SW1 | 5 | 2 | – | – | – | 7 | 6.23 | 2.98 | – | – | – | 9.21 | 1.2 | 1.5 | – | – | – | 1.25 | 1.3 |
| SW2 | 14 | 3 | 2 | – | – | 19 | 24.7 | 6.28 | 3.18 | – | – | 34.16 | 1.76 | 2.09 | 1.59 | – | – | 1.19 | 0.76 | 1.0 |
| SW3 | 15 | 3 | 1 | – | – | 19 | 23.1 | 7.1 | 3.6 | – | – | 33.8 | 1.54 | 2.37 | 3.60 | – | – | 1.54 | 1.52 | 1.5 |
| SW4 | 4 | 2 | 1 | 1 | – | 8 | 5.34 | 0.18 | 8.45 | 4.41 | – | 18.38 | 1.34 | 0.18 | 4.23 | 4.4 | – | 0.13 | 23.50 | 1.04 | 8.2 |
| SW5 | 8 | 5 | 3 | 3 | 1 | 20 | 6.86 | 6.39 | 1.74 | 9.3 | 4.15 | 28.44 | 0.86 | 1.28 | 0.58 | 3.1 | 4.2 | 1.49 | 0.45 | 5.34 | 1.35 | 2.2 |
| SW6 | 3 | 1 | 1 | – | – | 5 | 6 | 7.84 | 6.41 | – | – | 20.25 | 2.00 | 7.84 | 6.41 | – | – | 3.92 | 0.82 | 2.4 |
| SW7 | 29 | 6 | 1 | 1 | – | 37 | 42.2 | 15.1 | 2.04 | 15.3 | – | 74.76 | 1.46 | 2.52 | 2.04 | 15.3 | – | 1.73 | 0.81 | 7.50 | 3.3 |
| SW8 | 15 | 3 | 1 | – | – | 19 | 15.4 | 28.9 | 3.85 | – | – | 48.18 | 1.03 | 9.63 | 3.85 | – | – | 9.35 | 0.40 | 4.9 |
| SW9 | 15 | 4 | 1 | – | – | 20 | 27.7 | 15.4 | 9.36 | – | – | 52.51 | 1.85 | 3.86 | 9.36 | – | – | 2.09 | 2.42 | 2.3 |
| SW10 | 12 | 1 | – | – | – | 13 | 17.4 | 17.9 | – | – | – | 35.38 | 1.45 | 17.99 | – | – | – | 12.41 | 12.4 |
| SW11 | 11 | 2 | 1 | – | – | 14 | 17.4 | 0.3 | 17.1 | – | – | 34.79 | 1.58 | 0.15 | 17.10 | – | – | 0.09 | 114 | 57.0 |
| SW12 | 19 | 4 | 1 | 1 | – | 25 | 24.8 | 8.85 | 8.1 | 5.97 | – | 47.72 | 1.31 | 2.21 | 8.10 | 5.97 | – | 1.69 | 3.67 | 0.74 | 2.0 |
| SW13 | 22 | 8 | 2 | 1 | – | 33 | 45.8 | 45.6 | 10.2 | 5.83 | – | 107.3 | 2.08 | 5.70 | 5.10 | 5.83 | – | 2.74 | 0.89 | 1.14 | 1.6 |
| SW14 | 12 | 3 | 1 | – | – | 16 | 6.23 | 2.98 | – | – | – | 34.16 | 2.09 | 6.60 | 2.44 | – | – | 3.16 | 0.37 | 1.8 |
| SW15 | 14 | 3 | 1 | – | 18 | 24.7 | 6.28 | 3.18 | – | – | 34.16 | 2.09 | 6.60 | 2.44 | – | – | 3.16 | 0.37 | 1.8 |
observed (Table 1) that the maximum frequency is in case of first-order streams \((N_0 = 198)\) and decreases as the stream order increases \((N_0 = 1)\). This study also confirmed Horton’s law of \(N_0\) (1945); there is an inverse geometric correlation between \(u\) and the logarithm scale of \(N_u\) across the area of interest (Fig. 3a and 4). It was believed that the variation observed in the respective parameters was governed by the physiographic difference and structural condition of the watershed (Nikhil Raj and Azeez 2012; Praveen et al. 2018; Biswas 2016). The consistent decrease in \(N_u\) against \(u\) revealed the presence of erosional landform throughout the watershed (Avijit 2019).

**Stream length \((L_u)\)**

\(L_u\) and slope of any watershed are highly correlated to each other; streams with smaller \(L_u\) indicate the area is characterized as steep slope and vice versa (Withanage et al. 2014; Dubey et al. 2015; Christopher et al. 2010). Hence, \(L_u\) is considered as a useful hydrological feature to understand surface runoff characteristics as it is dependent on slope. The \(L_u\) of Tikur Wuha river watershed was accounted for 646.7 km with fifth order of 4.15 km and first order of 317.42 km (Table 1). In general, the plot of the logarithm of \(L_u\) versus \(u\) (Fig. 3b) showed some deviation from its general
behavior (linear pattern) indicates that the terrain is characterized by variation in lithology and topography (Nageswara et al. 2010). The logarithm scale of $L_{UT}$ is inversely correlated with $u$ for each SW (Fig. 5). More deviation ($r^2 < 0.5$) was observed in six SWs (SW4–8, 11) subjected to varied rock (parent) material, and the remaining nine SWs were characterized with homogeneous rock material (Nageswara et al. 2010).

**Mean stream length ($L_{um}$)**

$L_{um}$ of the study area was ranged from 0.15 (SW11) to 18 km (SW10). It is directly proportional to the size and topography of a drainage basin (Mangesh 2015). The mean stream length ratio ($L_{urm}$) was found between 1 (SW2) and 57 (SW11) (Table 1). Variation was also observed in stream length ratio ($L_{um}$), among successive stream orders. This variation revealed that the watershed was characterized by varying topography and slope according to Strahler (1964) and Gutema et al. (2017). Hence, it has an important control on discharge and erosional stage of the watershed (Sreedevi et al. 2004).

**Bifurcation ratio ($R_b$)**

The mean bifurcation ratio ($R_{bm}$) of the study watershed was ranged between 2 and 12. The higher the value of $R_b$ implies there is strong structural control on the drainage pattern (Nag and Chakraborty 2003). Referring Table 3, SW10 with high value of $R_{bm}$ was developed over easily erodible steeply dipping that also indicates high overland flow and discharge.

**Fig. 5** Regression of $L_{um}$ on $u$ for each SW
(Biswas 2016; Gajbhiye et al. 2015; Rawat et al. 2012). High \( R_b \) indicates early hydrograph peak with a potential for flash flooding during the storm events which results in degradation of top soil (Ajaykumar et al. 2019). The rest of the Tikur Wuha SWs (2 < \( R_{bm} < 5 \)) were less affected by the underlying geological disturbance and relatively characterized by high permeability and low erodibility (Pankaj and Kumar 2009). However, soil permeability may also be affected by other watershed parameters like shallow soil depth and less structural control on the catchment development (Asiamah et al. 2000; Kotei et al. 2015). The value of \( R_b \) is also indicative of the shape of the basin. Elongated basin, which is likely to have higher \( R_{br} \), yields a low but extended peak flow, while circular basins with low \( R_b \) procure sharp peak (Gajbhiye et al. 2015; Harinath and Raghu 2013).

### Rho coefficient (\( \rho \))

\( \rho \) is an important parameter which assists the evaluation of storage capacity of drainage network and, hence, a determinant of ultimate degree of drainage development in a given watershed (Horton 1945). Climatic, geologic, biologic, geomorphological and anthropogenic factors determine the changes in \( \rho \) (Chaitanya and Kanak 2015). \( \rho \) values of the study watershed are ranging between 0.3 and 15 for SW2 and SW15, respectively (Table 3). This implies higher hydrological storage during floods and attenuation of effects of erosion during elevated discharge.

### Watershed geometry features

#### Drainage area (\( A \)) and perimeter (\( P \))

The size of storm hydrograph and runoff magnitude are directly affected by the generated basin area (Strahler 1957); hence hydrologically, it is an important parameter. The SW’s \( A \) value is ranged between 11.14 and 89.25 km\(^2\) with perimeter (it is the length of the SW boundary) measured from 22.8 to 60.35 km, respectively, for SW1 and SW15 (Tables 4 and 5).

#### Shape factor ratio (\( B_s \))

\( B_s \) is the qualitative representation of a watershed that affects the stream discharge pattern. And it was expressed as the inverse of \( R_f \). The computed value of \( B_s \) is ranging between 3.7 and 13.5 for SW11 and SW9, respectively. The greater the circular character of the basin is, the greater is the rapid response of the watershed after a storm event (Tucker and Bras 1997). Therefore, in terms of \( B_s \), SW9 has the longest basin lag time and SW11 the shortest.

#### Form factor ratio (\( R_f \))

Basis with high \( R_f \) is characterized by peak flow of shorter duration, whereas elongated watershed with low \( R_f \) has lower peak flow with longer duration (Gajbhiye et al. 2015). In this study, maximum \( R_f \) was 0.27 for SW11 and minimum value 0.07 for SW9. The result shows that SW9 relatively more elongated the other SWs.

### Table 3 Bifurcation ratio, mean bifurcation ratio and Rho coefficient

| SW    | Bifurcation ratio (\( R_b \)) | Mean \( R_b \) (\( R_{bm} \)) | Rho coefficient, (\( \rho \)) |
|-------|------------------------------|-------------------------------|-----------------------------|
| I/II  | II/III                       | III/IV                        | IV/V                        |
| SW1   | 2.5                          | 2.5                           | 0.5                         |
| SW2   | 4.7                          | 1.5                           | 3.1                         |
| SW3   | 5                            | 3.0                           | 4                           |
| SW4   | 4                            | 2.0                           | 2.7                         |
| SW5   | 1.6                          | 1.7                           | 1.0                         |
| SW6   | 3                            | 1.0                           | 2                           |
| SW7   | 4.8                          | 6.0                           | 3.9                         |
| SW8   | 5                            | 3.0                           | 4                           |
| SW9   | 3.8                          | 4.0                           | 3.9                         |
| SW10  | 12                           | 12                            | 1.0                         |
| SW11  | 5.5                          | 2.0                           | 3.8                         |
| SW12  | 4.8                          | 4.0                           | 3.3                         |
| SW13  | 2.8                          | 4.0                           | 2.9                         |
| SW14  | 4                            | 3.0                           | 3.5                         |
| SW15  | 4.7                          | 3.0                           | 3.9                         |

Kotei et al. 2015).
Elongation ratio \((R_e)\)

The \(R_e\) values of near 1 indicate that there are less geomorphological controls on river basin (Strahler 1964). A circular basin is more efficient in runoff discharge than an elongated basin (Singh and Singh 1997). The \(R_e\) values of Tikur Wuha SW were varied from 0.31 to 0.59. The result indicated that SW9 and SW10 are more elongate than others implying low peak discharge, whereas SW2, SW3 and SW11 were relatively circular in nature (Avijit 2019).

Circularity ration \((R_c)\)

The \(R_c\) is an important tool to understand the geomorphological development stage of tributary basins. It varies depending on the lithological characteristics and other morphometric parameters of specific basin. \(R_c\) value of 0.42 (maximum) was calculated for SW3 indicative of circular shape, moderate to high relief and permeable surface relatively with old development stage. A minimum \(R_c\) value of 0.15 was assigned for SW10 that indicates elongated, low relief and

---

**Table 4** Watershed geometry parameters

| SW  | Basin length \((L_b)\) | Area \((A)\) | Perimeter \((P)\) | Shape factor ratio \((B_s)\) | Form factor \((R_f)\) | Elongation ratio \((R_e)\) | Circularity ratio \((R_c)\) | Compactness constant \((C_c)\) | Fitness ratio \((F_f)\) | Length area relation \((L_{ar})\) |
|-----|-----------------------|-------------|-----------------|--------------------------|----------------|--------------------------|---------------------------|--------------------------|----------------|---------------------------|
| SW1 | 8                     | 11.14       | 22.8            | 5.7                      | 0.17           | 0.47                     | 0.27                      | 1.93                     | 0.35            | 5.9                       |
| SW2 | 11                    | 30.15       | 30.94           | 4.0                      | 0.25           | 0.56                     | 0.40                      | 1.59                     | 0.36            | 10.8                      |
| SW3 | 12                    | 33.61       | 31.86           | 4.3                      | 0.23           | 0.55                     | 0.42                      | 1.55                     | 0.38            | 11.5                      |
| SW4 | 9                      | 14.28       | 24.6            | 5.7                      | 0.18           | 0.47                     | 0.30                      | 1.84                     | 0.37            | 6.9                       |
| SW5 | 13                    | 29          | 45.95           | 5.8                      | 0.17           | 0.47                     | 0.17                      | 2.41                     | 0.28            | 10.6                      |
| SW6 | 11                    | 17.1        | 28.88           | 7.1                      | 0.14           | 0.42                     | 0.26                      | 1.97                     | 0.38            | 7.7                       |
| SW7 | 22                    | 43.4        | 43.92           | 11.2                     | 0.09           | 0.34                     | 0.28                      | 1.88                     | 0.50            | 13.4                      |
| SW8 | 19                    | 47.97       | 45.77           | 7.5                      | 0.13           | 0.41                     | 0.29                      | 1.86                     | 0.42            | 14.3                      |
| SW9 | 22                    | 35.83       | 46.14           | 13.5                     | 0.07           | 0.31                     | 0.21                      | 2.17                     | 0.48            | 12.0                      |
| SW10| 21                    | 34.14       | 53.86           | 12.9                     | 0.08           | 0.31                     | 0.15                      | 2.60                     | 0.39            | 11.6                      |
| SW11| 14                    | 52.72       | 53.52           | 3.7                      | 0.27           | 0.59                     | 0.23                      | 2.08                     | 0.26            | 15.1                      |
| SW12| 21                    | 63.6        | 55.79           | 6.9                      | 0.14           | 0.43                     | 0.26                      | 1.97                     | 0.38            | 16.9                      |
| SW13| 19                    | 43.51       | 44.5            | 8.3                      | 0.12           | 0.39                     | 0.28                      | 1.90                     | 0.43            | 13.5                      |
| SW14| 18.6                  | 49.38       | 42.47           | 7.3                      | 0.14           | 0.42                     | 0.34                      | 1.70                     | 0.44            | 14.5                      |
| SW15| 25                    | 89.25       | 60.35           | 7.0                      | 0.14           | 0.43                     | 0.31                      | 1.80                     | 0.41            | 20.7                      |

**Table 5** Drainage parameters of the study area

| SW  | Drainage density \((D_d)\) | Length of overland flow \((L_g)\) | Stream frequency \((F_s)\) | Drainage intensity \((I_d)\) | Infiltration number \((I_f)\) | Drainage texture \((D_t)\) | Constant channel maintenance \((C)\) |
|-----|---------------------------|----------------------------------|---------------------------|-----------------------------|-----------------------------|----------------------------|-----------------------------------|
| SW1 | 0.83                      | 0.60                             | 0.63                      | 0.76                        | 0.52                        | 0.31                       | 1.21                             |
| SW2 | 1.13                      | 0.44                             | 0.63                      | 0.56                        | 0.71                        | 0.61                       | 0.88                             |
| SW3 | 1.01                      | 0.50                             | 0.57                      | 0.56                        | 0.58                        | 0.60                       | 0.99                             |
| SW4 | 1.29                      | 0.39                             | 0.56                      | 0.43                        | 0.72                        | 0.33                       | 0.78                             |
| SW5 | 0.98                      | 0.51                             | 0.69                      | 0.70                        | 0.68                        | 0.44                       | 1.02                             |
| SW6 | 1.18                      | 0.42                             | 0.29                      | 0.25                        | 0.34                        | 0.17                       | 0.84                             |
| SW7 | 1.72                      | 0.29                             | 0.85                      | 0.49                        | 1.46                        | 0.84                       | 0.58                             |
| SW8 | 1.00                      | 0.50                             | 0.40                      | 0.40                        | 0.40                        | 0.42                       | 1.00                             |
| SW9 | 1.47                      | 0.34                             | 0.56                      | 0.38                        | 0.82                        | 0.43                       | 0.68                             |
| SW10| 1.04                      | 0.48                             | 0.38                      | 0.37                        | 0.40                        | 0.24                       | 0.96                             |
| SW11| 0.66                      | 0.76                             | 0.27                      | 0.41                        | 0.18                        | 0.26                       | 1.52                             |
| SW12| 0.75                      | 0.67                             | 0.39                      | 0.52                        | 0.29                        | 0.45                       | 1.33                             |
| SW13| 2.47                      | 0.20                             | 0.76                      | 0.31                        | 1.88                        | 0.74                       | 0.41                             |
| SW14| 1.02                      | 0.49                             | 0.32                      | 0.31                        | 0.33                        | 0.38                       | 0.98                             |
| SW15| 0.58                      | 0.87                             | 0.20                      | 0.34                        | 0.12                        | 0.30                       | 1.74                             |
impermeable surface with a young stage of geomorphological adjustment (Ajaykumar et al. 2019).

**Compactness coefficient ($C_c$)**

The $C_c$ value of a basin is inversely related with $R_e$ (Waikar and Aditya 2014; Zakaria et al. 2016). In this study, the $C_c$ varies from 1.55 to 2.6 (Table 3). The lower value of $C_c$ in the case of SW3 was the indication of more elongation and less erosion, while the reverse was observed in SW10, that is, the higher the $C_c$ value, the lower the elongation and the higher the erosion occurrence probability. The $C_c$ directly corresponds to its infiltration capacity (Ajaykumar et al. 2019).

**Fitness ratio ($F_f$)**

The $F_f$ value of the study is varied between 0.26 and 0.5 for SW11 and SW7, respectively. It is a measure of topographic fitness (Praveen et al. 2018; Melton 1957).

**Length area relation ($L_{ar}$)**

In this study, the $L_{ar}$ is ranged from a maximum of 20.7 for SW15 to a minimum value of 5.9 for SW1. $L_{ar}$ is an important geometric parameter to understand the association between stream length and basin area (Hack 1957).

**Drainage texture attributes**

**Drainage density ($D_d$)**

Because of its wide ratio of variation, drainage density is a number of primary importance in landform scale analysis (Strahler 1957). According to Melton in 1957, high value of $D_d$ indicates highly dissected catchment with a relatively rapid hydrological response to rainfall, while a low drainage density expresses a poorly drained basin with a slow hydrological response.

Figure 6 indicates the $D_d$ distribution map generated based on Smith (1950) and Chandrashekar et al. (2015) classification range. $D_d$ is one of the factors controlling the surface runoff and consequently influences the output of sediment and water from the basin (Chorley 1969). In general, as the $D_d$ number increases, the size of individual drainage units, such as the first-order drainage basin, decreases proportionately (Strahler 1957). The lower drainage density of any watershed indicates streams are widely spaced and low erosion occurrence is expected (Ajaykumar et al. 2019).

**Stream frequency ($F_s$)**

$F_s$ is directly correlated with $D_d$; the lesser the $F_s$ indicates less $D_d$ resulted in low runoff value, and hence, flooding is less likely to occur (Thomas et al. 2010). $F_s$ depends on the rainfall, relief, as well as drainage density of the basin. In the study, SW’s $F_s$ value (Tables 4 and 5) is ranged from 0.2 to 0.85 numbers per km². Low $F_s$ indicates that the watershed has less rocky terrain and very high infiltration capacity which contributes toward less erosion (Ajaykumar et al. 2019; Avijit 2019). The higher $F_s$ value of 0.85 numbers per km² in SW7 indicated that the area was dominated by high slope and low permeability. Low value of $F_s$ was observed in SW6 and SW11 that reveals the sub-watersheds were characterized by less relief and low slope ranges.

**Drainage texture ($D_t$)**

$D_t$ is an important fluvial parameter which denotes the relative spacing of drainage network of any basin (Avijit 2019). $D_t$ is affected by the amount of rainfall, density of vegetation, soil types, infiltration capacity, stages of geomorphic development and relief (Horton 1945; Smith 1950). Based on Smith (1950) classification range, the $D_t$ less than 2
indicates very coarse, between 2 and 4 is related to coarse, between 4 and 6 is moderate, between 6 and 8 is fine and greater than 8 is very fine drainage texture. The $D_i$ of the entire area was below 2 indicating very coarse texture range (Tables 4 and 5), which implies higher permeability and enhanced groundwater (Albaroot et al. 2018). Regions of low infiltration capacity will give rise to higher $D_i$ and thus will lead to more erosion (Ajaykumar et al. 2019). In this study, minimum value was accounted for SW6 that revealed the SW is plain with lower degree of slopes, while maximum $D_i$ value indicates the SW was associated with high degree of slope (SW7 for instance) as noted by Gajbhiye et al. (2015).

**Length of overland flow ($L_g$)**

$L_g$ is one of the most important independent variables affecting both the hydrological and physiographic development of drainage basins. Referring Tables 4 and 5, a higher value of $L_g$ (SW15) represents low relief, whereas a low value of $L_g$ (SW7 and SW13) is an indicative of high relief (Biswas 2016). $L_g$ is directly related to average slope of drainage channel; hence, the greater the value, more is the erosion severity in the case of SW15 (Ajaykumar et al. 2019).

**Constant of channel maintenance ($C$)**

The lower value of $C$ indicates higher flood potentiality and young geomorphological adjustment. Steep slope area generally has low $C$ values due to lower infiltration of bare soil. The calculated $C$ value is varied between minimum of 0.41 for SW13 and maximum of 1.74 for SW15 (Tables 4 and 5). Low $C$ value for SW13 revealed that the SW is associated with very low-resistance and low infiltration capacity of bare soils; sparse vegetation and mountainous (steep slope) terrain resulted in high overland flow and high flood potentiality (Farrukh et al. 2013; Avijit 2019).

**Relief aspect**

**Basin relief ($H$)**

$H$ indicates the erosional stage of a river basin, and it varies relaying upon the underlain geology, geomorphology and drainage characteristics of particular region. Mountain–Plain front river basin has higher basin relief than plateau–Plain front river basin (Thomas et al. 2010). The elevation of Tikur Wuha river basin ranged from 1643 m (SW5, the outlet to Lake Hawassa) in the northwestern part to 2976 m (SW15) in the southern part of the study area (Fig. 1). In the present study, the maximum $H$ value is 988 m for SW13 indication of susceptibility for erosional activity and the minimum was 95 m for SW6.

**Relief ratio ($R_r$)**

The $R_r$ indicates the overall slope of the watershed surface (Strahler 1964) and also tells us the average drop in elevation per unit length of the stream. According to Ajaykumar et al. (2019), high $R_r$ values indicate high rate of stream flow and erosion vulnerability due to high sediment loss. As confirmed by Schumm in 1954, $R_r$ is useful in estimating sediment yield. The value obtained here varied from 0.01 (for SW5 and SW6) to 0.07 for SW3.

**Ruggedness number ($R_n$)**

The $R_n$ value implies the susceptibility of watershed to soil erosion (Gutema et al. 2017). Ruggedness values range between zero and one, values nearer to 0 refer to relatively smoother situation, and those nearer to 1 show more rugged terrain characteristics. The higher the values of $D_a$ and $H$ are, the higher the value of $R_n$ will become. As a result, the slope is not only steep but long. Referring to Table 6, SW13 with higher value of $D_a$ and $H$ scores the maximum $R_n$ value 2.44 and SW6 with the minimum amount, that is, 0.11.

**Slope and aspect of the watershed**

The slope gradient directly influences the formation of drainage networks, and it enables the assessment of runoff generation, direction and amount (Zavoiance 1985). The runoff speed from a particular basin is dependent on the associated slope range, thereby affecting the required time for rainwater to enter in the stream beds (Mesa 2006). The slope of the study watershed varies from 0° to 73° and reclassified (Fig. 7). There is a high slope gradient in the eastern parts (northeast and southeast) because of the presence of high relief causing rapid runoff, increasing erosion rates, and low recharge potential. As slope determines the infiltration vs runoff relation, it is important to understand the nature of slope in any region. Infiltration capacity is inversely related to the slope (Avijit 2019).

The result obtained from the correlation index (Table 7) indicated that relatively there is a strong correlation between drainage texture parameters. The two watershed geometry attributes: $C_e$ and $R_n$, are inversely correlated to each other. Strong positive correlation was also observed between $R_c$ and $R_f$, $L_g$ and $D_a$ were correlated inversely to each other. It is well correlated with $L_g$ in opposite manner, and $D_i$ was highly correlated with $F_s$. Direct relationship was identified between $L_g$ and $I_g$, $D_i$ is more strongly correlated with the $R_{hp}$ of the watershed.
Based on the data from Geological Survey of Ethiopia, majority of the underlying area (Fig. 7c) is dominated by Pleistocene–Holocene, undifferentiated followed by lacustrine sediments where commonly created as a result of precipitation of salts dissolved in the lake water (Gilbert 1978) and a river or stream channel has carried sediment into the basin. Alkaline and peralkaline silicics are also found. Ignimbrites are of low density and high porosity, are very weak to weak in compression and have low tensile (Vicki 1993).

Table 6 Relief aspects of Tikur Wuha river basin

| SW   | Lowest height ($z$) | Highest height ($Z$) | Basin relief ($R_b$) | Relief ratio ($R_r$) | Ruggedness number ($R_n$) | Relative relief ($R_{hp}$) | Dissection index ($D_{is}$) |
|------|---------------------|----------------------|----------------------|---------------------|---------------------------|-----------------------------|-----------------------------|
| SW1  | 1678                | 1869                 | 191                  | 0.02                | 0.16                       | 0.8                         | 10                          |
| SW2  | 1678                | 2087                 | 409                  | 0.04                | 0.46                       | 1.3                         | 20                          |
| SW3  | 1690                | 2525                 | 835                  | 0.07                | 0.84                       | 2.6                         | 33                          |
| SW4  | 1678                | 1933                 | 255                  | 0.03                | 0.33                       | 0.5                         | 13                          |
| SW5  | 1643                | 1869                 | 226                  | 0.02                | 0.22                       | 0.4                         | 12                          |
| SW6  | 1678                | 1773                 | 95                   | 0.01                | 0.11                       | 0.3                         | 05                          |
| SW7  | 1681                | 2639                 | 958                  | 0.04                | 1.65                       | 2.2                         | 36                          |
| SW8  | 1678                | 2661                 | 983                  | 0.05                | 0.98                       | 2.1                         | 37                          |
| SW9  | 1692                | 2673                 | 981                  | 0.04                | 1.44                       | 2.1                         | 37                          |
| SW10 | 1678                | 2495                 | 817                  | 0.04                | 0.85                       | 1.5                         | 33                          |
| SW11 | 1678                | 2237                 | 559                  | 0.04                | 0.37                       | 1.0                         | 25                          |
| SW12 | 1679                | 2454                 | 775                  | 0.04                | 0.58                       | 1.4                         | 32                          |
| SW13 | 1685                | 2688                 | 1003                 | 0.05                | 2.48                       | 2.3                         | 37                          |
| SW14 | 1882                | 2687                 | 805                  | 0.04                | 0.82                       | 1.9                         | 30                          |
| SW15 | 2182                | 2976                 | 794                  | 0.03                | 0.46                       | 1.3                         | 27                          |

Fig. 7 Slope distribution (a) and aspect (b) and geological (c) map

Geological feature

Based on the data from Geological Survey of Ethiopia, majority of the underlying area (Fig. 7c) is dominated by Pleistocene–Holocene, undifferentiated followed by lacustrine sediments where commonly created as a result of precipitation of salts dissolved in the lake water (Gilbert 1978) and a river or stream channel has carried sediment into the basin. Alkaline and peralkaline silicics are also found. Ignimbrites are of low density and high porosity, are very weak to weak in compression and have low tensile (Vicki 1993).

Conclusions

In this study, hydrological perspectives of morphometric parameters were assessed on Tikur Wuha river watershed. The result obtained indicated that there are spatial variability and correlation among the morphometric attributes, and hence, the study addressed the hydrological characteristics relying on the different attributes. The study area was characterized with low infiltration capacity as it has higher $u$ value. In general sense, the watershed is in the state of undergoing/active erosion and matured topography development. Some
Table 7  Correlation matrix among different morphometric parameters

|          | $R_{bm}$ | $\rho$ | $A$   | $R_f$ | $R_s$ | $R_c$ | $C_c$ | $F_f$ | $L_{uf}$ | $D_a$ | $L_g$ | $F_s$ | $I_d$ | $I_f$ | $D_t$ | $R_r$ | $R_n$ | $R_{hp}$ | $D_{is}$ |
|----------|----------|-------|-------|-------|-------|-------|-------|-------|----------|-------|-------|-------|-------|-------|-------|-------|-------|----------|-------|
| $R_{bm}$ | 1.00     |       |       |       |       |       |       |       |          |       |       |       |       |       |       |       |       |          |       |
| $\rho$   | -0.03    | 1.00  |       |       |       |       |       |       |          |       |       |       |       |       |       |       |       |          |       |
| $A$      | 0.05     | 0.06  | 1.00  |       |       |       |       |       |          |       |       |       |       |       |       |       |       |          |       |
| $R_f$    | -0.35    | 0.54  | -0.09 | 1.00  |       |       |       |       |          |       |       |       |       |       |       |       |       |          |       |
| $R_s$    | -0.42    | 0.50  | -0.04 | 0.99  | 1.00  |       |       |       |          |       |       |       |       |       |       |       |       |          |       |
| $R_c$    | -0.38    | -0.21 | 0.06  | 0.49  | 0.51  | 1.00  |       |       |          |       |       |       |       |       |       |       |       |          |       |
| $C_c$    | 0.53     | 0.15  | -0.14 | -0.43 | -0.46 | -0.96 | 1.00  |       |          |       |       |       |       |       |       |       |       |          |       |
| $F_f$    | 0.11     | -0.60 | 0.14  | -0.73 | -0.73 | 0.17  | -0.24 | 1.00  |          |       |       |       |       |       |       |       |       |          |       |
| $L_{uf}$ | 0.08     | 0.06  | 0.99  | -0.10 | -0.05 | 0.05  | -0.12 | 0.15  | 1.00     |       |       |       |       |       |       |       |       |          |       |
| $D_a$    | -0.12    | -0.29 | -0.35 | -0.39 | -0.41 | -0.41 | -0.01 | 0.63  | -0.88    | 1.00  |       |       |       |       |       |       |       |          |       |
| $I_g$    | 0.06     | 0.39  | 0.67  | 0.38  | 0.42  | -0.04 | 0.49  | 0.63  | -0.88    | 1.00  |       |       |       |       |       |       |       |          |       |
| $F_s$    | -0.19    | -0.31 | -0.42 | -0.12 | -0.13 | 0.07  | -0.37 | 0.73  | -0.75    | 1.00  |       |       |       |       |       |       |       |          |       |
| $I_d$    | -0.16    | -0.06 | -0.15 | 0.39  | 0.41  | 0.07  | -0.12 | 0.21  | 0.07     | 0.49  | 1.00  |       |       |       |       |       |       |          |       |
| $I_f$    | -0.16    | -0.27 | -0.27 | -0.29 | -0.31 | 0.03  | -0.07 | 0.43  | -0.22    | 0.95  | -0.81 | 0.87  | 0.05  | 1.00  |       |       |       |          |       |
| $D_t$    | -0.22    | -0.34 | 0.00  | -0.06 | -0.05 | 0.38  | -0.38 | 0.42  | 0.06     | 0.63  | -0.54 | 0.84  | 0.38  | 0.80  | 1.00  |       |       |          |       |
| $R_r$    | 0.23     | -0.04 | 0.18  | 0.15  | 0.14  | 0.47  | -0.39 | 0.24  | 0.25     | 0.17  | -0.11 | 0.23  | 0.15  | 0.23  | 0.52  | 1.00  |       |          |       |
| $R_n$    | 0.11     | -0.26 | 0.10  | -0.50 | -0.51 | 0.00  | -0.05 | 0.66  | 0.17     | 0.83  | -0.62 | 0.56  | -0.24 | 0.82  | 0.69  | 0.51  | 1.00  |          |       |
| $R_{hp}$ | 0.22     | -0.30 | 0.29  | -0.27 | -0.27 | 0.36  | -0.33 | 0.65  | 0.36     | -0.29 | 0.30  | -0.08 | 0.40  | 0.63  | 0.86  | 0.76  | 1.00  |          |       |
| $D_{is}$ | 0.39     | -0.15 | 0.48  | -0.39 | -0.40 | 0.06  | -0.06 | 0.58  | 0.55     | 0.26  | -0.11 | 0.16  | -0.11 | 0.30  | 0.48  | 0.77  | 0.74  | 0.91     | 1.00  |
SWs were characterized circular in nature and are most susceptible to rapid hydrological response due to the shortest time of concentration. Hydrological process and underlying materials are mainly correlated with Dd and Fs, and the lower the values indicated less rocky terrain and very high infiltration capacity which contributes toward less erosion (for example: SW11). With the aim of water resource planning, the findings of this investigation will provide core ideas to identify groundwater potential zones; to study flood risk assessment; and to select suitable sites for the construction of water harvesting structures.

Acknowledgements This study was supported by Hawassa University Office of Vice President for Research and Technology Transfer, and we would like to acknowledge the office. The authors are also thankful to the academic and financial staffs from Wondo Genet College of Forestry and Natural Resources, Hawassa University.

Funding For this study, funding was provided by Hawassa University Office of Vice President for Research and Technology Transfer.

Compliance with ethical standards

Conflict of interest The authors declared that there is no conflict of interest in this study.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Ajaykumar KK, Tasadof HJ, Sanjay SK, Bhavana NU, Rabindranath NS (2019) Identification of erosion-prone areas using modified morphometric prioritization method and sediment production rate: a remote sensing and GIS approach. Geon Nat Hazards Risk 10(1):986–1006. https://doi.org/10.1002/gnh.25705.2018.155189

Albaroot M, Nabil MA, Hamdi SA, Mohamed A, Saleh AG (2018) Quantification of morphometric analysis using remote sensing and GIS techniques in the Qa’ Jahran Basin, Thamar Province, Yemen. Int J New Technol Res (IJNTR) 4(8):12–22

Ali H, Hassan K (2018) Morphometric, statistical, and hazard analyses using ASTER data and GIS technique of WADI El-Mathula watershed, Qena, Egypt

Asiamah RD, Adjei-Gyapong T, Yeboah E, Fening JO, Ampountah EO, Gaisie E (2000) Soil characterization and evaluation of four primary cassava multiplication sites (Mampong, Wenchi, Asutuare and Kpeve) in Ghana. SRI Technical Report No. 200, Kumasi

Avijit M (2019) The significance of morphometric analysis to understand the hydrological and morphological characteristics in two different morpho-climatic settings. Appl Water Sci 10:33. https://doi.org/10.1007/s13201-019-1118-2

Ayele AF, Hiroshi Y, Katsuyuki Sh, Nigussie H, Kifle W (2017) Quantitative analysis and implications of drainage morphometry of the Agula watershed in the semi-arid northern Ethiopia. Appl Water Sci 7:3825–3840. https://doi.org/10.1007/s13201-017-0534-4

Benuankantha D, Nagaraju MSS, Sahu N, Nasre RA, Mohankar DS, Srivastava S, Singh SK (2019) Morphometric analysis for planning soil and water conservation measures using geospatial technique. Int J Curr Microbiol Appl Sci 8(01):2719–2728. https://doi.org/10.20546/ijcmas.2019.801.287

Bharadwaj AK, Pradeep C, Thirumalaivasan D, Shankar CP, Madhavan N (2014) Morphometric analysis of Adyar watershed. IOSR J Mech Civ Eng (IOSR-IMCE), e-ISSN: 2278-1684, p-ISSN: 2320–334X. www.iosrjournals.org

Biswas SS (2016) Analysis of GIS based morphometric parameters and hydrological changes in Parbati River Basin, Himachal Pradesh, India. J Geogr Nat Disast 6:1675. https://doi.org/10.4172/2167-0587.1000175

Chaitanya BP, Kanak M (2015) GIS based quantitative morphometric analysis and its consequences: a case study from Sharun River Basin, Maharashtra India. Appl Water Sci 7:861–871. https://doi.org/10.1007/s13201-015-0298-7

Chandrashekar H, Lokesh KV, Sameena M, Roopa J, Ranganna G (2015) In: Dwarakish GS (Elsevier Procedia) (eds) Proceedings of the International Conference on Water Resources, Coastal and Ocean Engineering (Mangalore) vol 4. Pp 1345–1353

Chorley RJ (1969) Introduction to physical hydrology. Methuen and Co. Ltd., Suffolk, p 211

Christopher O, Idowu A, Olugbenga A (2010) Hydrological analysis of Onitha North East drainage Basin using geoinformatic techniques. World Appl Sci J 11(10):1297–1302

Diakakis M (2010) A method for flood hazard mapping based on basin morphometry: application in two catchment in Greece. Nat Hazards 56(3):803–814. https://doi.org/10.1007/s11069-010-0959-8

Dubey SK, Sharma D, Mundetia N (2015) Morphometric analysis of the Banas River Basin using geographical information system, Rajasthan, India. Hydrology 3(5):47–57. https://doi.org/10.11648/j.hyd.20150305.11

ESRI (2011) Arc Hydro Tools—Tutorial Version 2.0, United States of America www.esri.com

Fannir A (1968) The index of drainage intensity—a provisional new drainage factor. Austral J Sci 31:328–330

Farrukh A, Gowhar M, Romshoo SA (2013) Morphometric analysis to infer hydrological behaviour of lidder watershed, Western Himalaya, India. Hindawi Publishing Corporation, Geography Journal, London. https://doi.org/10.1155/2013/178021

Gajul MD, Mujawar KC, Unhale PL, Prabhakar P (2016) Prioritization of Balatira Watershed by morphometric and landuse landcover analysis, Atpadi Taluka, Sangli District, Maharashtra. J Appl Geol Geophys 4(3)

Geena GB, Ballukraya PN (2011) Morphometric analysis of Koratilaayar River basin, Tamil Nadu, India: A GIS approach. Int J Geom Geosci 2(2). ISSN 0976-380

Gilbert R (1978) Lacustrine sedimentation. In: Sedimentology. Encyclopedia of Earth Science. Springer, Berlin, Heidelberg

Gravelius H (1914) Flusskunde. Goschen Verlagshaus diung Berlin. In: Zavoinaia I (ed) Morphometry of drainage basins. Elsevier, Amsterdam

Gutema D, Kassa T, Sifan AK (2017) Morphometric analysis to identify erosion Prone areas on the upper blue Nile using GIS
for water resource management based on remote sensing data. Appl Water Sci 8:15. https://doi.org/10.1007/s13201-018-0660-7
Rawat KS, Mishra AK, Tripathi VK (2012) Hydro-morphometrical analyses of sub-Himalayan region in relation to small hydro-electric power. DOI, Arab J Geosci. https://doi.org/10.1007/s12517-012-0586-6
Schumm SA (1956) The evolution of drainage systems and slopes in Badlands at Perinth Amboy, New Jersey. Geological Society of America Bulletins 67:597–646
Singh S, Dubey A (1994) Geo-environmental planning of watershed in India. Chugh Publications, Allahabad. pp 28–69
Singh S, Singh MC (1997) Morphometric analysis of Kanhar river basin. Nat Geogr J India 43(1):31–43
Smith KG (1950) Standards for grading textures of erosional topography. Am J Sci 248:655–668
Sreedevi PD, Subrahmanyam K, Ahmed S (2004) The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. Environ Geol 47:412–420
Strahler AN (1957) Quantitative analysis of watershed geomorphology. Trans Am Geophys Union 38:913–920
Strahler AN (1964) Quantitative geomorphology of drainage basins and channel networks. In: Ven Te Chow (ed) Handbook of applied hydrology, pp 439–476
Tesfaye M, Wondimun M (2014) Morphometric analysis of Didessa River catchment in Blue Nile Basin, Western Ethiopia. Sci Technol Arts Res J. https://doi.org/10.4314/star.v3i3.31
Thomas J, Joseph S, Thirivikramaj KP (2010) Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India. Int J Digit Earth 3(2):135–156
Tucker GE, Bras RL (1997) The role of rainfall variability in drainage basin evaluation: implication of stochastic model. EOS Trans AGU 78:283
Vicki GM (1993) Geotechnical characteristics of ignimbrite: a soft pyroclastic rock type. Eng Geol. https://doi.org/10.1016/0013-7952(93)90068-N
Waikar ML, Aditya PN (2014) Morphometric analysis of a drainage basin using geographical information system: a case study. Int J Multidiscip Curr Res 2:179184
Withanage NS, Dayawansa NDK, De Silva RP (2014) Morphometric analysis of the Gal Oya River Basin using spatial data derived from GIS. Trop Agric Res 26(1):175–188
Wolka K, Mengistu T, Taddese H, Tolera A (2014) Impact of land cover change on water quality and stream flow in Lake Hawassa Watershed of Ethiopia. Agric Sci 5:647–659
World Meteorological Organization (2003) The associated program on Integrated Flood Management: Case of Ethiopia: Integrated Flood Management, Technical Supprt Init, Kefyalew Achameyleh (ed). www.apfm.info/pdf/case_studies/cs_ethiopia.pdf
WWDSF (2001) The study of Lake Awassa level, lake Awassa study and design project. Water Works Design and Supervision Enterprise, Addis Ababa
Yacob E (2010) Evaluating the impact of land use land cover change on soil erosion and runoff using SWAT model at Tikur Wuha watershed. Unpublished master’s thesis, Addis Ababa, Ethiopia
Yangchan J, Jain AK, Tiwari AK, Sood A (2015) Morphometric analysis of drainage basin through GIS: a case study of Sukhna Lake Watershed in Lower Shiwalik, India. Int J Sci Eng Res 6(2)
Zakaria M, Abul Kashem M, Majadur R (2016) Morphometric analysis of Reju Khal drainage basin using geographic information system (GIS) and SRTM data. Int J Sci Eng Res 7(6). ISSN 2229-5518
Zavoiance I (1985) Morphometry of drainage basins (development in geomorphology). Bull Geol Soc Am 56:275–370
Zhu MJ, Song AM (2010) Image processing and analysis of sub-Himalyan region in relation to small hydro-electric power. DOI, Arab J Geosci. https://doi.org/10.1007/s12517-012-0586-6
Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.