# GEOMORPHOLOGIC CHARACTERITICS OF NZOIA RIVER BASIN

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## ABSTRACT

Relationships between geomorphologic characteristics are important in understanding runoff response of many drainage basins and other related flow driven basin phenomena like erosion potential. In Kenya, geomorphologic studies are few and therefore inadequate. Nzoia basin in which this study is based is no exception. Nzoia River basin is the largest sub-basin in the Lake Victoria North basin of Kenya. However, geomorphology as a component of the basin's general physical characteristics has not been studied and its linkage to flooding established. This study aimed at finding a geomorphologic explanation for the run-off response in the Nzoia River basin. The methodology involved is characterizing the basin using indices like: relief ratios, stream orders, bifurcation ratios, drainage density and form factor.

The study concluded that there is no consistent relationship between relief ratio and basin order in this basin due to high variance in relief on the divide line. However, high relief ratios of above 0.03 are observed as characteristics of upland subbasins and low value of about 0.01 for subbasins at the lowlands. This change has explained the flooding phenomena at the lowlands. Bifurcation ratios ranged from 2.8 and 3.3 which are within Strahler's range but average value of 3.1 is closer to the lower bound value of 2. On the basis of bifurcation ratio, Nzoia basin flows may experience delayed time to peak and this is a good property for planning flood response strategies. Analysis of drainage density distribution has shown uniform conveyance efficiency with a mean value of $0.24^{-km}$, however, theoretically, the value lacks control values to base judgment. Overall form factor has classified the basin as fern-shaped with possibility of delayed high peaked hydrographs which is also important for flood evacuation planning.

**Key words:** Stream order, bifurcation ratio, form factor, drainage density

## 1.0 INTRODUCTION

Land morphometry represents the topographic representation of land by way of area, slope, shape, length etc.. These parameters affect catchment streamflow pattern through their influence on concentration time. Strahler (1964) groups morphometric relationships into three: (1) linear morphometric relationships, e.g, bifurcation ratio, length ratio, etc (2) areal morphometric relationships, e.g, law of stream areas, drainage density etc and (3) relief morphometric indices e.g. maximum relief, relief ratio, ruggedness number etc.

From fundamentals of hydrologic sciences(e.g. Chow *et al.*(1988), it is known that watershed run-off is a response function of rainfall input in a water basin. Watershed runoff is composed of three components (surface run-off, sub-surface run-off and base flow), which may be at a given time occur separately or simultaneously with varying magnitudes. This variation is a function of climatic characteristics of input rainfall, geomorphologic characteristics of the basin and man made interferences including forest cover changes. The three run-off components finally converge into a stream to form streamflow, which is usually characterised by hydrograph function. In other words, a hydrograph, which is a flow-time graph, is an integral expression of all those factors, which govern the relationship between rainfall and runoff of a particular drainage basin.

It is a common approach in many rainfall-runoff relationship studies to draw conclusions on the basis of meteorological factors only. Geomorphologic characteristics of many drainage basins and their relationship with runoff response in Kenya are poorly described or still unknown. However, a number of studies on geomorphological implications on hydrology have been studied elsewhere (e.g. Nyadawa and Muiruri (2001); Patton; (1988), Iturbe, (1982) just to mention a few. Patton, working with various basins in North America developed basin specific regression formulae for predicting floods based on ruggedness number, relief ratio, first order channel frequency and basin magnituds. However, these are non transferrable relationships. Nyadawa and Muiruri explained the discrepancy of runoff response in two subbasins in Upper Athi in reference differences in bifurcation ratios and form factors but like other previous studies elsewhere the relationships are non transferrable. Though most previous studies have relied on topographic sheets to generate topographic data for geomorphologic analysis, it should be appreciated that recent advent of GIS and availability of DEM data from open data sources has now made it possible to generate channel networks and other geomorphologic forms from DEM thereby complementing field survey data which is typically static and costly to obtain. A study by McNamara *et al.* (2006) used this technique to mark geomorphologic thresholds for erosion potential of the Pang Khum Experimental Watershed in northern Thailand.

A number of studies (JICA, 1987; JICA, 1992; APFM, 2004; ADCL, 2006) have been carried out in Nzoia basin with a view to characterizing the basin on the basis of climatic data and land use information but none has incorporated landform parameters because geomorphologic studies have not been attempted. Recent government proposal to manage flood hazard in the basin by adoption of integrated flood management strategy (ADCL, 2006) will need a comprehensive characterization of the basin on the basis of all variables. The communities who live in the lowland zone of River Nzoia continue to experience annual flood disasters due to failure of structural flood mitigation systems like earth dykes in controlling high flows. Destruction of natural forest cover in the middle and upper zones of Nzoia catchment continue unabated. The linkage between geomorphology and increased incidences of flood disaster is poorly understood amongst planners and communities occupying the basin. Therefore, the objective of this study is to establish geomorphic characteristic of Nzoia basin with reference to a few commonly used morphometric parameters of relief ratio, bifurcation ratio, drainage density and form factor. The authors understand that the full scope of geomorphology goes beyond these four parameters but assumes that the four parameters will provide a basic geomorphic understanding of the area for planners.

Nzoia system is the largest river basin in Kenya's Lake Victoria basin and has its source in the forested highlands (Mt. Elgon, Cherangani hills, Nandi Hills and Kakamega forest). Geographically, the basin is situated between latitudes $1^0$ 30'N and $0^0$ 05'S and between longitudes $34^0$E and $35^0$ 45'E with an area of 12,709km$^2$ and a length of 334km up to its outfall into the Lake Victoria. River Nzoia experiences perennial flooding in its lower reaches especially the Budalangi area of Busia district. Mean annual discharge of River Nzoia is estimated at $1777 \times 10^6$m$^3$/year by ADCL(2006). From physiographic and land use point of view, the basin has four distinct zones: mountain zone, plateau zone, transition zone and lowland zone. Mountain zone is forested but suffers severe land degradation; plateau zone is the major farming zone. Small-scale farming continues in the transition and the flood prone lowland area.

## 2.0 METHODOLOGY AND DATA

Major input data for this study are: digital elevation model for the basin (DEM), and shape file of river networks.

1) *Digital Elevation Model*
   This spatial terrain dataset at a resolution of 90x90m was obtained from the Shuttle Radar Topography Mission (SRTM) data (FAO, 2004) which in turn is archived as open data source by USGS EROS at a website (http://edcdaac.usgs.gov/gtopo30/hydro/africa.html). Figure. 2 shows clipped DEM for the basin.

2) River network shapefile was clipped from Kenya's River network shapefile available were based on the work of JICA (1992) and confirmed by streams-grid theme file generated by complete Terrain Analysis of the basin with DEM shown in Figure. 2 as an input in USGS Geo-SFM model.

Sub-basins were rationalised to coincide with those adopted by Water Resources Management Authority.

Four morphological parameters were used to characterize the basin as follows:

(i). Relief ratio as derived from Digital Elevation Model of the basin was analyzed both at overall and sub-basin scale in a GIS environment. Relief ratio ($R_h$) is given by equation (1), which is defined as the ratio of maximum basin relief (H) to horizontal distance along the longest dimension of the basin parallel to the principal drainage line ($L_b$) (Schumm, 1956). It is a non dimensionless parameter which measures the steepness of a watershed and can therefore, be related to its hydrologic characteristic.

$$R_h = \frac{H}{L_b} \quad \text{--------------------------------------------------------------------------(1)}$$

Maximum basin relief (H) and basin length ($L_b$) were measured by query tools in ArcView. Sixteen sub-basins out of the total twenty three sub-basins as delineated by Ministry of Water and Irrigation were selected for Relief ratio analysis. Ignored sub-basins are receiving their flow inputs from upstream sub-basin and therefore contained streams in the basin are not starting from order one.

(ii).Bifurcation ratio ($R_b$) expressed by Equation 2 is stream segmentation index proposed by Horton (1945) in his law commonly referred to as Horton's Law of Stream numbers which states that the number of stream segments of each order *Mwangi* constitutes an inverse geometric sequence with order number as expressed mathematically by equation 2. Theoretically, It gives an idea about the shape of the resulting hydrograph. $R_b$ between consecutive orders in a basin approach a constant value which is the $R_b$ of the basin. Amongst different basins it is known that as $R_b$ decreases, peak discharge increases and time to peak decreases.

$$R_b = \frac{N_w}{N_w + 1} \quad \text{--------------------------------------------------------------------------(2)}$$

Where $N_w$ is number of streams of order w and $N_w$+1 is number of streams of order w+1. Theoretical minimum value of the bifurcation ratio is 2, and values typically lie in the range of 3-5 (Strahler, 1964). In this case numbers were counted physically from drainage network shapefile superimposed on subbasin shapefile.

iii. Drainage density (D) expressed by Equation 3 is an indicator of surface runoff conveyance efficiency. It is the ratio of total length of streams draining a particular drainage basin to its area and therefore, it has a dimension ($L^{-1}$) (Smart,1972). It is a measure of dissection of a basin and reflects the competing effectiveness of overland flow and infiltration. Low drainage density is associated with run-off processes dominated by infiltration and subsurface flow, while basins of high drainage densities are products of erosion and dissection by overland flow. For basins of comparative relief, the hydrologic response of a stream network is directly related to drainage density.

$$D = \frac{\sum_{i=1}^{k}\sum_{i=1}^{N} L_u}{A_u} \text{------------------------------------------------------------------(3)}$$

Where D is the ratio of total channel-segment lengths ( $L_u$ ) cumulated for all orders i=1 to k within a basin to the basin area ( $A_u$ ).

For drainage density analysis, all the twenty three subbasins were considered as downstream order effect is irrelevant.

iv. Form factor ( $R_f$ )(Horton,1932): is a ratio of basin area () to the square of basin length (). Horton proposed form factor in order to express basin shape quantitatively. However, other indices have since been suggested without significant advantage. Examples are circulator ratio (Miller, 1953) and elongation ratio (Schumm, 1956). This study used form factor as expressed by Equation 4 because of the ease of measuring independent variables. This shape factor may be interpreted in reference to basin flooding potential in a comparative analysis as low values of form factors are associated with fern-shaped basin with large time of concentration and long lag time.

$$R_f = \frac{A_u}{L_u^2} \text{---- ---------------------------------------------------------------------------(4)}$$

In this case drainage areas of subbasin were measured by ArcView measurement tools by delineating subbasins along divides in the drainage basin's shapefile. However, basin length are determined as earlier explained for relief ratio.

## 3.0 RESULTS AND DISCUSSION

DEM of the basin as shown in Figure.2 indicates that relief of the study basin range from 4304 m at the river outlet to the lake to 1146 m at the uplands, resulting in an average maximum basin relief of 3158 m with a basin length of 205,610 m resulting in a basin relief ratio of about 0.0153. Results of Relief ratios and stream order analysis for the composing subbasins are indicated in Table 1 and Figure 5. Results of relief ratios in Table 1 are derived from same DEM superimposed on subbasin boundaries as shown in Figure 3. Superimposition of drainage network on DEM is necessary for the computation of stream orders at subbasin level. Table 2 is simply a statistical summary of data given in Table 1.

Relief ratio is a non dimensionless parameter which measures the steepness of a watershed and can therefore, be related to its hydrologic characteristic. In this case, it is observed that all subbasins whose divide line pass through the upper mountain ranges (e.g.DB, BH and BE in case of Mt. Elgon) have high relief ratios of above 0.03 and this drops drastically to a low value of about 0.01 for sub-basins at the lowlands (see values relief ratio values for EG, EB, DD in Table 1). This means that short lag time, high peak hydrographs from the upper reaches must change their translation time characteristics as the flood wave move through the lowlands. It is not within the scope of this study to quantitatively determine the relationship between this change in relief ratio and change in wave celerity or water velocity during this transition. However, it worth noting that this reduction in relief induces an increase in flow depth if flow width is kept constant or increased flow width (inundated width) incase flow depth cannot be increased due to topographic restrictions. In other words this geomorphic characteristics as explained by relief ratio favors field experience of common flooding at Nzoia delta.

Table 2 which was derived from Table 1 by averaging relief ratios of all sub-basins of similar order revealed that there is negative gradient from order one to two(see Fig. 6 for fall in relief ratio from higher value in order one to a less value in order two) which agrees with normal trends in basins of uniform relief at the divide, given that basin length increases in magnitude with increase in basin order in such cases. However, this theory of uniformity of relief at the divide does not hold beyond order 2 as we observe upward trend in relief ratios from order 2, 3 and 4, therefore creating two bands of trends (1-2 and 3-4). This leads to the conclusion that there is no consistency between relief ratio and basin order in Nzoia and no uniformity of relief at the divide. This is attributed to high variance of relief on the divide as earlier stated in the subchapter of introduction which identified major relief on the divide as Mt.Elgon, Cherangani hills, Nandi Hills and Kakamega forest, all at varying altitudes. The inconsistency in relief ratio–basin order relationship is also supported by high percentage deviation indices in Table 2 which actually ranges from 21% for order 4 to 45% in order 2. Sub-basins on the Eastern side (see basin codes starting with letter C in Table 1) show low values of relief ratio compared to those located in the West (see basin codes starting with letter B in Table 1) where altitude is rather high. Using the highest relief in the analysis 2893m at DB and a basin length of 334km, the mean relief ratio of Nzoia basin at order 5 is approximately 0.009 which is far smaller value and indicator of mild gradient at the lower reaches of the river which is the flooding area. Though the generalized relationship between relief ratio and basin order is not found for the whole basin, comparative relations between basin relief of upper basins and lowland basin is given.

The basis of computation of Bifurcation is determination of basin orders at the subbasin level. As stated earlier in methodology, bifurcation ratio is the basis of Horton's law of stream numbers (Equation 2). The law of stream numbers is an expression of topological phenomenon and shows only a small variation from one region to another because watersheds in homogeneous materials tend to manifest geometric similarity. Therefore, the ratio theoretically range between 3 and 5 and can be used as an index of hydrograph shape for watersheds similar in other respects. In this study, Figure 5 shows sample river order computation steps which were followed for the whole basin of river network shown in Figure . 4. Substituting basin order values shown in Table 1 in equation 2 resulted in bifurcation ratios displayed in Table 3. From Table 1, it is established that the basin orders in Nzoia range from 1 to 4 and being that there are more than two sub-basins of order 4 found in the overall analysis and they all drain in one main channel, it means by induction that the total basin order at the river entry to the lake is 5.

Computation of bifurcation ratios (see Table 3) shows that the values ranged from 2.8 and 3.3 which is within Strahler's range**.** Strahler (1964) argued that, bifurcation ratios characteristically range between 3 and 5 with value of 2 as minimum for watersheds in which the geologic structures do not distort the drainage pattern. In this case, the average bifurcation ratio for the basin is 3.1 which is an almost a lower bound value in Strahler's range. Revisiting the hypothesis stated in methodology that as $R_b$ decreases, peak discharge increases and time to peak decreases, low value of $R_b$ may be explained in the reverse all other factors remaining constant. On the basis bifurcation ratio, Nzoia basin may experience delayed time to peak on the incoming hydrographs and this good property for planning evacuations or communicating flood forecasts. This conclusions is based on the premise that geologic structures do not distort the drainage pattern of Nzoia basin but this need to be supported by a comprehensive geologic study.

Using a basin area of 12,709 km$^2$ and a basin length of 334 km, the form factor which is a ratio of basin area to the square of basin length is approximately 0.1 which is smaller value compared 0.7 which is the value if the basin is hypothetically converted to square shape. Square shape with one mid drainage channel is a theoretical base shape where the effect of length and width of a basin are equal. This low value confirms the fern shape of Nzoia basin. Such shapes depict delayed hydrograph peaks, however elongated basins are unlikely to realize uniform rainfall over the entire basin at same time. This means delayed lag time should be factored in flood forecasting and evacuation planning in the basin. This finding is consistent with the previous argument advanced for bifurcation ratio.

Drainage Density is a measure of the closeness of channel spacing and therefore an indicative of drainage efficiency and length of overland flow as previously explained in methodology. The argument against this parameter is that it is not dimensionless and not static for any basin. For this reason the boundary values cannot be defined(Gardiner and Gregory, 1988). Gardiner and Gregory reported temporal variations of drainage density in basins studied by various researchers around the world and values ranged from 0.32 to 47.3. In this study Table 4 and Fig.7 show spatial distribution of drainage density in the entire basin. Visual inspection of density values in Table 4 and summary statistics of the table indicate relatively uniform spatial distribution drainage density values the basin (Data range of 0.11 – 0.45, mean=0.24 and Std= 0.09). The mean value of 0.24$^{-km}$ cannot be accurately be regarded as high or low in magnitude because of lack of boundary conditions. However, the drainage efficiency is rather uniform, the occurrence of floods in lower reaches of River Nzoia could be explained by other supporting parameters like relief ratio.

## 4.0 CONCLUSION

This study has explained geomorphic characteristics of Nzoia basin on the basis of four common indices.

(i). Computation of bifurcation ratios shows that the values ranged from 2.8 and 3.3 which are within Strahler's range but averagely the value is closer to the lower bound value of 2. On the basis of bifurcation ratio, Nzoia basin flows may experience delayed time to peak and this is a good property for planning evacuations or communicating flood forecasts.

(ii) Study on trends of relief ratios with basin orders revealed that high relief ratios of above 0.03 are characteristics of upland subbasins and this drops drastically to a low value of about 0.01 for subbasins at the low lands. This change has explained the flooding phenomena at the lowlands by postulating that this reduction in relief induces an increase flow width (inundated width) as flow depth cannot be increased in this zone of the basin due to topographic restrictions.

(iii) Analysis of drainage density distribution has shown uniform conveyance efficiency with a mean value of $0.24^{-km}$. However, theoretically, the value lacks control values to base judgment. For this limitation the interpretation in limited to spatial variability and frequent occurrence of floods is attriuted to effect of relief ratio.

(iv) Computation of shape index using form factor has classified the drainage basin as fern-shape.

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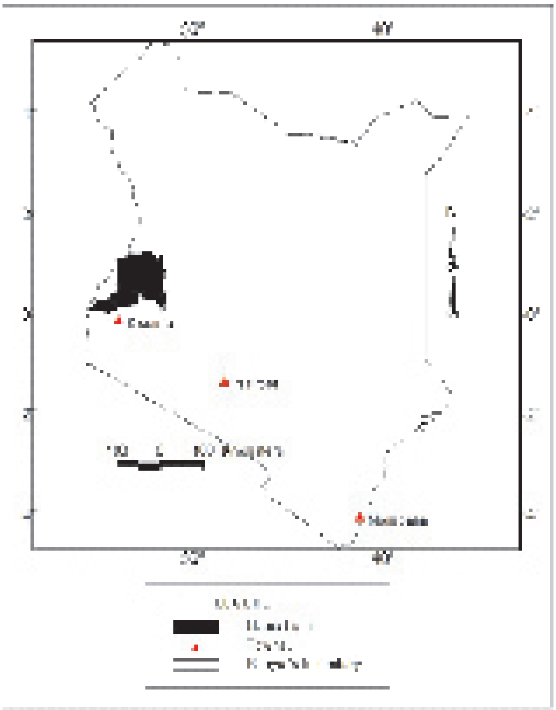


*Figure 1: Location map of Nzoia basin*

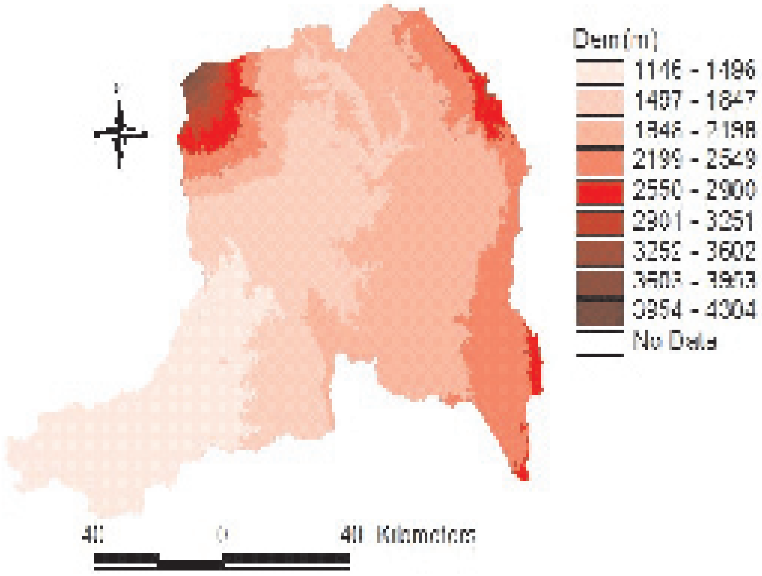


*Figure 2: Nzoia Basin DEM*
Source: http://edcdaac.usgs.gov/gtopo30/hydro/africa.html

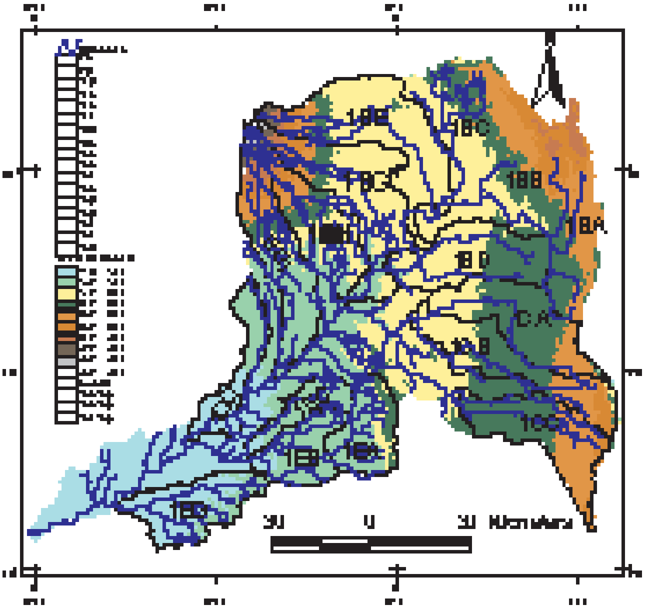
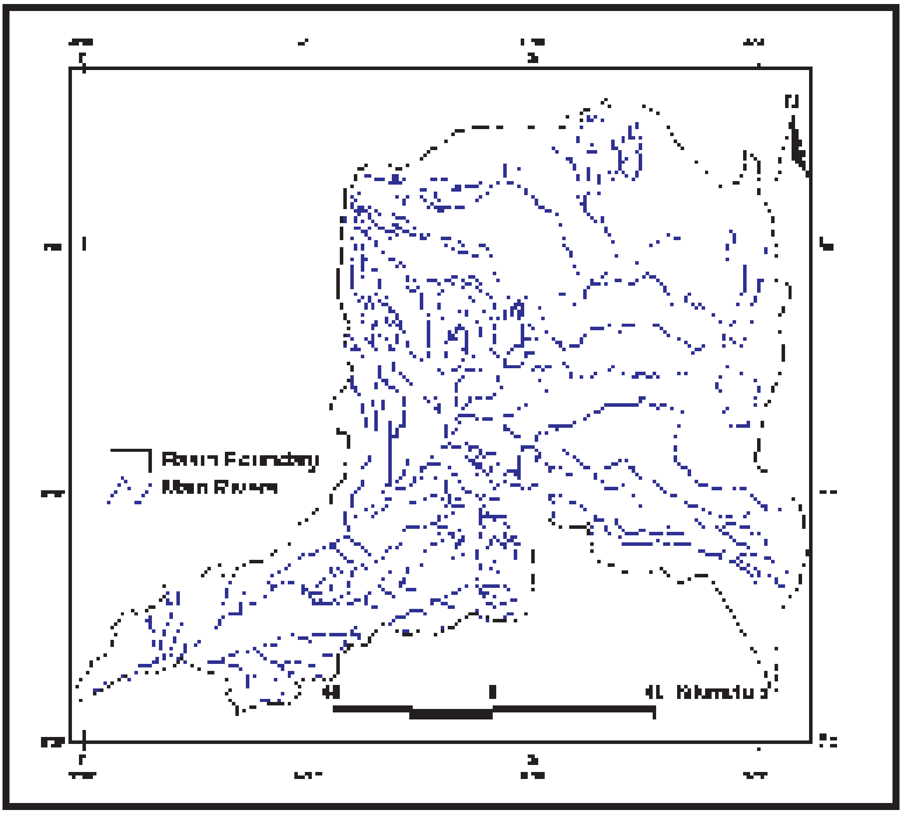


*Figure 3: Nzoia river network and sub-basins superimposed on basin DEM*



Note: Temporary or minor streams are omitted

*Figure 4: Nzoia river network*

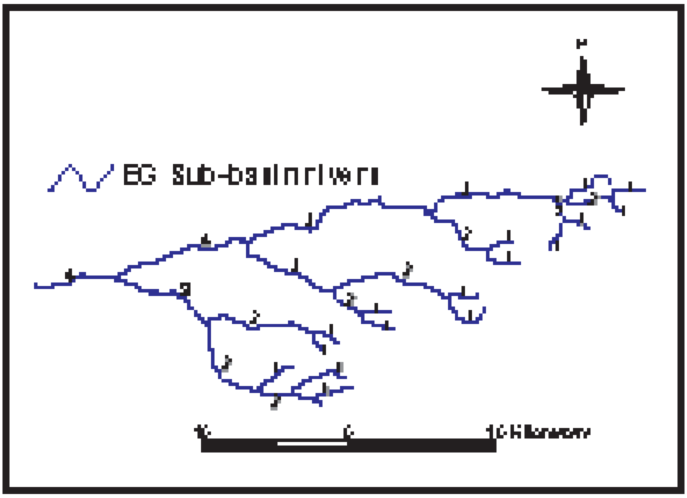


*Figure 5: Sample river order computation (sub-basin EG)*

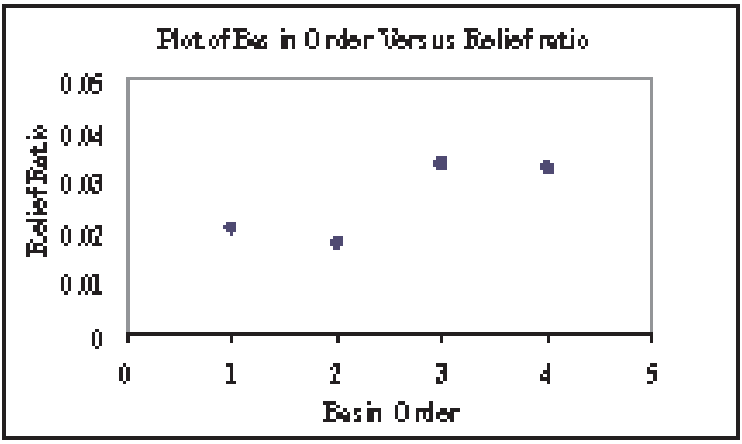


Figure 6: Average relief ratios ($\bar{R}_h$)versus sub-basin order at the standard sub-catchment scale as computed in Table 2

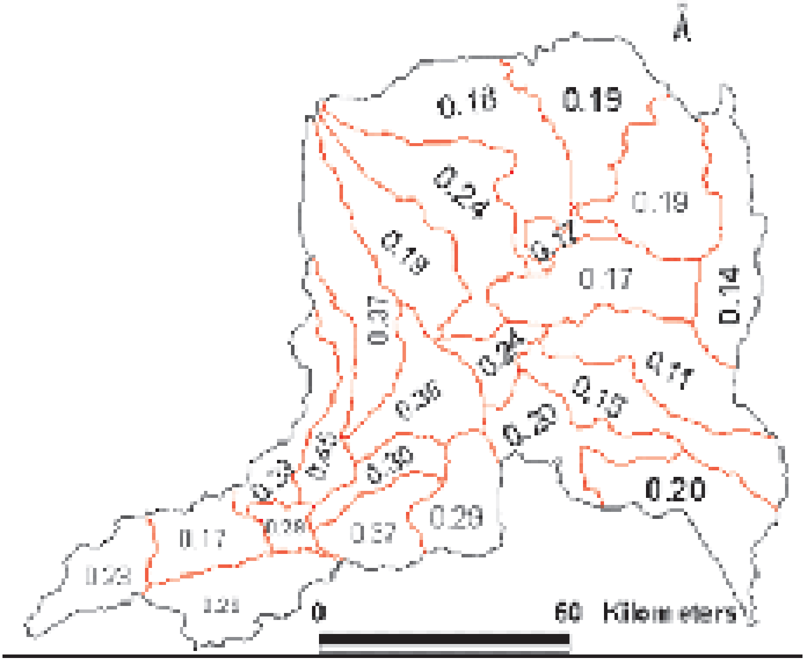
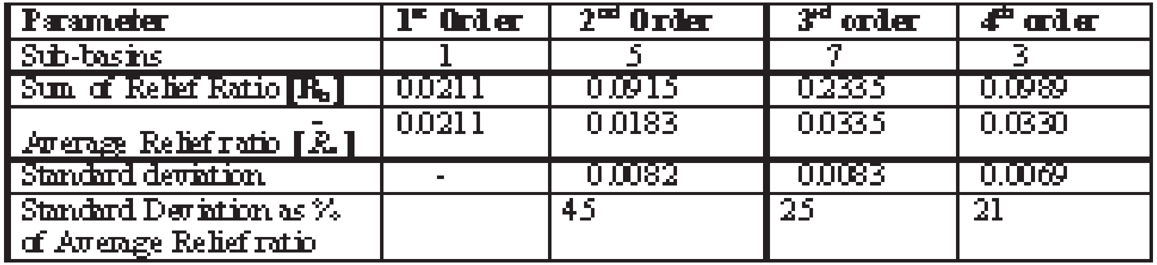


Figure 7: Spatial distribution of drainage densities within the basin

Table 1: Results of computed relief ratios and stream orders

| | | | | Stream Order no. | | | |
|---|---|---|---|---|---|---|---|
| Sub-Basin | Distance (m) [$L_b$] | Height H (m) | Relief ratio [$R_h$] | 1 | 2 | 3 | 4 |
| BA | 61800 | 1398 | 0.0226 | 4 | 1 | 0 | 0 |
| BB | 47560 | 1386 | 0.0291 | 1 | 1 | 0 | 0 |
| BC | 39120 | 1343 | 0.0343 | 20 | 4 | 2 | 1 |
| BD | 49730 | 542 | 0.0109 | 2 | 1 | 0 | 0 |
| BE | 59450 | 2127 | 0.0357 | 11 | 2 | 1 | 0 |
| BF | 61380 | 2402 | 0.0391 | 22 | 5 | 2 | 1 |
| BH | 64960 | 2542 | 0.0391 | 19 | 3 | 1 | 0 |
| | | | | | | | |
| CA | 59940 | 1265 | 0.0211 | 1 | 0 | 0 | 0 |
| CB | 71490 | 1410 | 0.0197 | 3 | 1 | 0 | 0 |
| CC | 48480 | 900 | 0.0186 | 11 | 5 | 1 | 0 |
| | | | | | | | |
| DB | 70180 | 2893 | 0.04122 | 13 | 3 | 1 | 0 |
| DD | 43650 | 402 | 0.0092 | 2 | 1 | 0 | 0 |
| | | | | | | | |
| EA | 24960 | 636 | 0.0255 | 15 | 5 | 2 | 1 |
| EB | 33450 | 392 | 0.0117 | 6 | 2 | 1 | 0 |
| EC | 38720 | 380 | 0.0098 | 8 | 3 | 1 | 0 |
| EG | 48780 | 342 | 0.007 | 16 | 9 | 4 | 2 |

Table 2: Average sub-basin relief ratios of similar order as computed from data in Table 1



| Parameter | 1st Order | 2nd Order | 3rd order | 4th order |
|---|---|---|---|---|
| Sub-basins | 1 | 5 | 7 | 3 |
| Sum of Relief Ratio $[R_b]$ | 0.0211 | 0.0915 | 0.2335 | 0.0989 |
| Average Relief ratio $[\bar{R}_b]$ | 0.0211 | 0.0183 | 0.0335 | 0.0330 |
| Standard deviation | - | 0.0082 | 0.0083 | 0.0069 |
| Standard Deviation as % of Average Relief ratio |  | 45 | 25 | 21 |

Table 3: Bifurcation ratios as computed from data in Table 1

| Order Number | Number of streams | Bifurcation Ratio |
|---|---|---|
| 1 | 154 | - |
| 2 | 46 | 3.3 |
| 3 | 16 | 2.8 |
| 4 | 5 | 3.2 |
| 5 | 1 | - |
| Average bifurcation ratio | | 3.1 |

Table 4: Computation of sub-basin drainage densities

| Sub-basin Code | Total stream length (km) | Area ($km^2$) | Drainage density ($km^{-1}$) |
|---|---|---|---|
| BA | 89.47 | 628.14 | 0.14 |
| BB | 105.34 | 616.32 | 0.17 |
| BC | 142.30 | 767.49 | 0.19 |
| BD | 116.88 | 676.28 | 0.17 |
| BE | 181.82 | 1007.89 | 0.18 |
| BG | 174.94 | 904.34 | 0.19 |
| BH | 158.51 | 862.93 | 0.18 |
| CA | 74.59 | 682.92 | 0.11 |
| CB | 98.35 | 670.41 | 0.15 |
| CC | 134.53 | 661.90 | 0.20 |
| CD | 101.90 | 520.11 | 0.20 |
| CE | 54.50 | 229.55 | 0.24 |
| DA | 184.37 | 518.15 | 0.36 |
| DB | 254.97 | 694.29 | 0.37 |
| DC | 165.28 | 371.39 | 0.45 |
| DD | 82.70 | 354.78 | 0.23 |
| EA | 125.87 | 427.43 | 0.29 |
| EB | 138.97 | 378.75 | 0.37 |
| EC | 75.04 | 249.16 | 0.30 |
| ED | 36.63 | 128.18 | 0.29 |
| EE | 67.38 | 399.37 | 0.17 |
| EF | 87.14 | 383.85 | 0.23 |
| EG | 143.19 | 542.15 | 0.26 |
| Drainage Density data range | | | 0.11-0.45 |
| Mean Drainage Density | | | 0.24 |
| Standard Deviation | | | 0.09 |