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GEOMORPHOLOGICAL AND DRAINAGE MORPHOMETRICAL RELATIONSHIP OF GEM POTENTIAL ALLUVIAL DEPOSITS IN UPPER *KALU GANGA* BASIN, SRI LANKA: A REMOTE SENSING AND GIS BASED APPROACH

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ABSTRACT

Several alluvial deposits in the *Kalu Ganga* basin are the most prominent secondary gem deposits in Sri Lanka. The quantitative morphometric analysis of watersheds is necessary to understand the hydrological setup of an area and the spatial distribution of alluvial formations. Since the processes involved in weathering, erosion, and sediment transport are directly imprinted on the land surface, an attempt was made to study drainage morphometry and morphology of the Upper *Kalu Ganga* basin to understand hydrologic processes that influenced the formation of secondary gem deposits. Digital Elevation Model (DEM) with GIS application and field observations were applied for the present study. Calculated linear, areal, and relief morphometric parameters of the basin indicate surface runoff, potential energy, susceptibility for soil erosion, denudation rate, sediment yield, and discharge rate are likely to be much higher in *Kalu Ganga* Head-watershed, *Rath Ganga*, and *Hangamu Ganga* while sediment deposition is higher in *Kuru Ganga* and *Katugas Ella*. The surface roughness studies enable to identify the localities of alluvial deposits that may carry gem-bearing sediments. Among the several methodologies used, multivariate analyses of morphometric parameters are the most viable and cost-effective for evaluating possible gem-bearing alluvial deposits on a regional scale, despite their limitations.

Keywords *Multivariate, Morphometric, alluvial gem deposits, river basin, Kalu Ganga*

1. INTRODUCTION

The majority of valuable gem stones in Sri Lanka are discovered in historic alluvial deposits. They are the durable residual debris brought from hilly locations as weathering products of basement high-grade crystalline metamorphic rocks, and they can be found in the beds of ancient rivers, valley bottoms, abandoned tributaries, and alluvial terraces as gem-baring gravel layers and sand layers (Nawarathne, 2014). Several gem deposits may have developed as a result of minerals transported across long distances (Kumara et al., 2015). Despite the fact that Sri Lanka includes a large number of gem pits and that gemstone mining has been conducted for centuries, a few studies have been conducted solely to determine the gem prospectivity (Fernando, 1995; Jayamali et al., 2017). Ratnapura gem field is the most dominant secondary gem field in Sri Lanka. Despite the fact that secondary gem deposits can occur as residual, eluvial, or alluvial deposits (Dahanayake et al., 1980), the Ratnapura gem field is dominated by alluvial deposits. Most of such deposits are associated with the *Kalu Ganga* basin. Therefore, the formation of which is influenced by catchment characteristics such as drainage pattern, land cover, morphology, relief, and slope, among others (Dar et al., 2013). However, all of such characteristics have not been considered for the demarcating alluvial deposits which may have gem-bearing sediments (Jayamali et al., 2017; Kumara et al., 2015; Ranasinghe et al., 2005).

Interpretations derived from remote sensing data, in particular, are extremely useful for identifying features of the physical environment developed in the past, as these have a high potential to be preserved on the present landscape (Moran et al., 1994). The automated derivation of topographic watershed data using Digital Elevation Models (DEM) with Geographical Information System (GIS) technique is a quick, reliable, and inexpensive way for calculating morphometric analysis (Akar, 2017; Sarangi et al., 2003; Tribe, 1992; Reddy et al. 2004; Sreedevi et al., 2005, 2009; Valeriano et al., 2006; Grohmann et al., 2007; Ozdemir and Bird, 2009; Brasington et al., 2012). Therefore, an attempt was made to use this approach to interpret the influence of drainage morphometry and morphology of the Upper *Kalu Ganga* basin in the Ratnapura area for the understanding of the occurrences of alluvial deposits.

2. STUDY AREA

Kalu Ganga basin is the second largest river basin in Sri Lanka covering 2766 km^2. It originates from the central highlands in the wet zone at an altitude of 2250 m above Mean Sea Level (MSL) and runs through the Western slopes and then the Western plains until it falls out to sea at Kalutara. The total traverse of *Kalu Ganga* is about 129 km. The average annual rainfall within the catchment is about 4000 mm (Ampitiyawatta, 2009; Panditharathne et al., 2019).

This study was carried out over the *Kalu Ganga* upper catchment area, which is situated between 179502N – 141350N and 151316E – 195014E in Sri Lankan national grid (projected coordinate system) at altitudes greater than 20 m (Fig. 1).

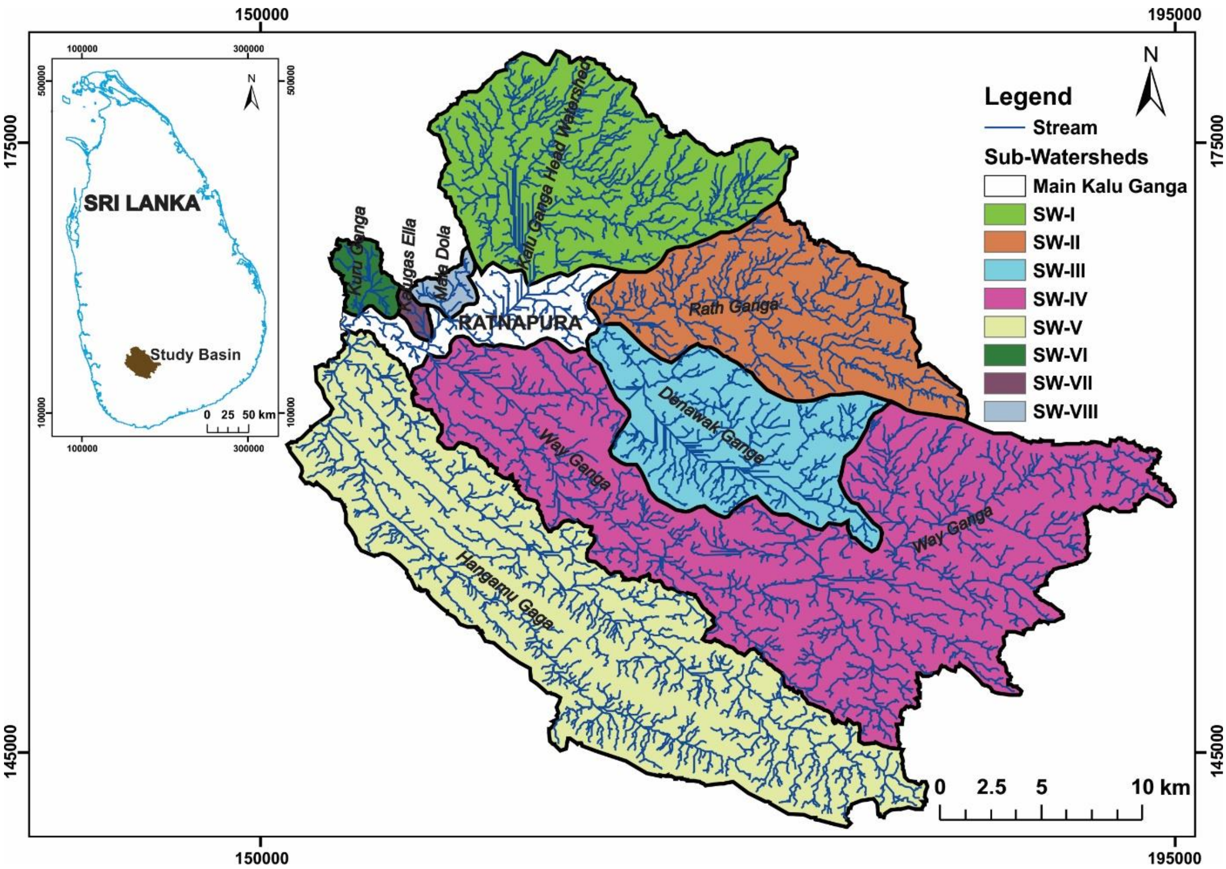

Fig. 1: *Map showing the Upper Kalu Ganga basin and its eight sub-watersheds studied in this research*

The total area of the studied sub-basin is approximately 881 km^2 and it is about 31.8% of the total catchment area of the basin. The elevation of the area ranges from 5 m to 1,965 m above mean sea level. In the upper part of the study basin, the gradients are steep (~ 45^0 - 69^0), while in the lower part, the gradients are mild (0^0 - 4^0). Major land use in the area consists of natural forests and forest plantations, as well as residential areas and agricultural cropland. The majority of the current overburden is residual, with a significant amount of colluvium deposited by landslides and minor alluvial occurrences primarily along the main river (Gunatilaka, 2007; Gunatilaka and Almond, 2001). According to the mapping by the Geological Survey and Mines Bureau, Sri Lanka (GSMB, 1995 – 1997), this area consists of high-grade Proterozoic metamorphic rocks. Among them, charnockitic biotite gneiss, granitic gneiss, and garnet sillimanite biotite ± graphite gneiss are the most abundant rocks. The occurrence of intrusive rocks of zircon-bearing granites, vein quartz, and pegmatites are also occasionally present (Cooray, 1984).

Based on the pour points where tributaries drain into the main river (*Kalu Ganga*), 8 sub-watersheds can be demarcated and they are named as *Kalu Ganga* Head-watershed (SW-I), *Rath Ganga* (SW-II), Denawak Ganga (SW-III), *Way Ganga* (SW-IV), *Hangamu Ganga* (SW-V), *Kuru Ganga* (SW-VI), *Katugas Ella* (SW-VII) and *Mala Dola* (SW-VIII) for the current study as shown in Fig. 1.

3. METHODOLOGY

This study was conducted based on the Advanced Space born Thermal Emission and Reflection Radiometer (ASTER) 30m Global Digital Elevation Model (GDEM) (Fig. 3) with absolute vertical accuracy within 0.20m on average (Tachikawa et al., 2011). 1:10,000 scale digital topographic data from the Survey Department of Sri Lanka (SDSL), and GPS data at the field were also used as inputs. Arc GIS 10.4.1 was used to generate, process, and integrate the digital spatial data.

This study was conducted via examination of the horizontal accuracy of ASTER GDEM, DEM quality improvement, drainage network delineation, quantitative morphometry in Arc GIS environment. The overall workflow is shown in Fig. 2.

3.1 Drainage Network Delineation and demarcation of river basins

The drainage network delineation was modeled via identifying and filling of DEM sinks, flow direction determination, and flow accumulation calculation in Arc GIS by using 3 x 3 window scan of the ASTER 30m GEM. A threshold value of 100 was used as the cumulative number of the upstream cells draining to each cell to define the stream network. The extracted drainage network was manipulated using natural drainage present in SDSL 1:10,000 digital topographic data to obtain the optimum drainage network. The widely used Strahler's method of stream ordering (Strahler, 1964) was followed to order the streams in the drainage network (Fig. 3).

The boundaries of the 8 sub-watersheds viz. *Kalu Ganga* Head-watershed (SW-I), *Rath Ganga* (SW-II), *Denawak Ganga* (SW-III), *Way Ganga* (SW-IV), *Hangamu Ganga* (SW-V), *Kuru Ganga* (SW-VI), *Katugas Ella* (SW-VIII), and *Mala Dola* (SW-VIII) were demarcated by defining pour point for each sub-watershed. Image processing techniques were applied to enhance the data in order to get the optimum sub-watershed basins for the analysis.

3.2 Morphometric Feature Analysis

In this study, morphometric characterization of the 8 sub-watersheds was performed in GIS environment. Firstly, the basin parameters, namely, number of streams, length of streams, elevation ranges, area, perimeter and basin length for all 8 sub-watersheds were calculated in GIS. Thereafter, the linear, areal and relief morphometric parameters were calculated as follows with established mathematical equations in Table 1.

3.2.1 Linear parameters

Linear morphometric parameters, namely, Stream order (U), Stream length (Lu), Biffercation Ratio (R_b) were computed.

3.2.2 Areal parameters

Areal morphometric parameters, namely, Drainage density (D_d), Stream frequency (F_s), Drainage texture (T), Elongation ratio (R_e), Form factor (F_f), Texture ratio (R_t) were computed.

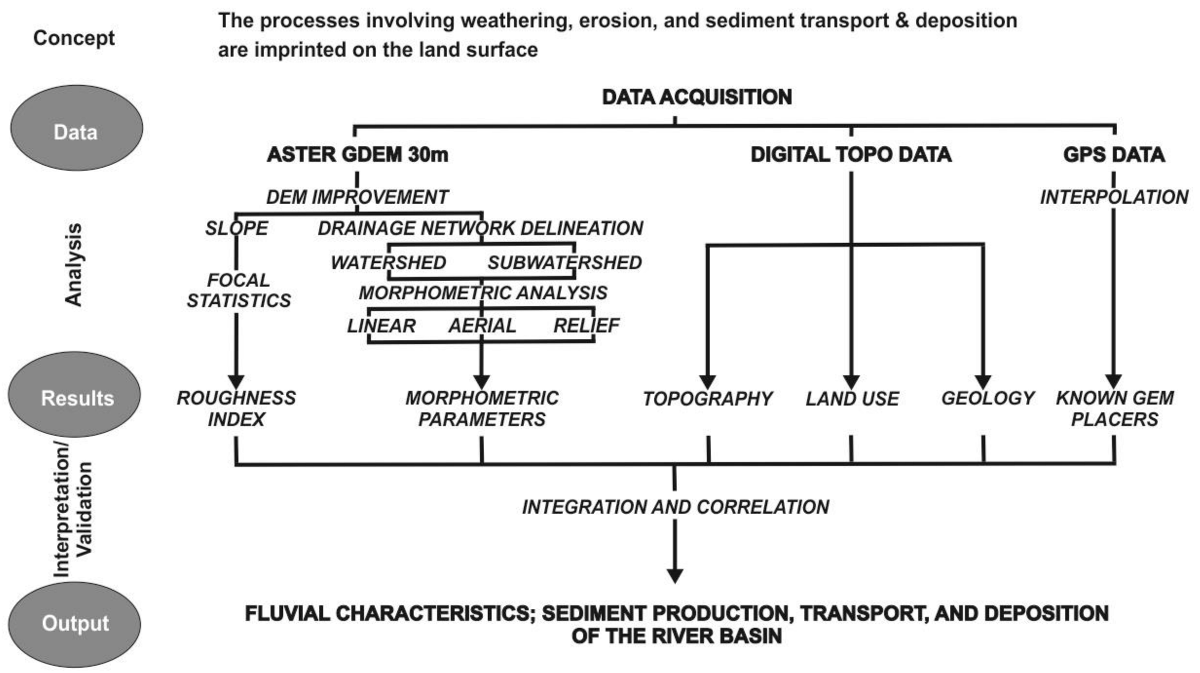

Fig. 2: *The workflow chart*

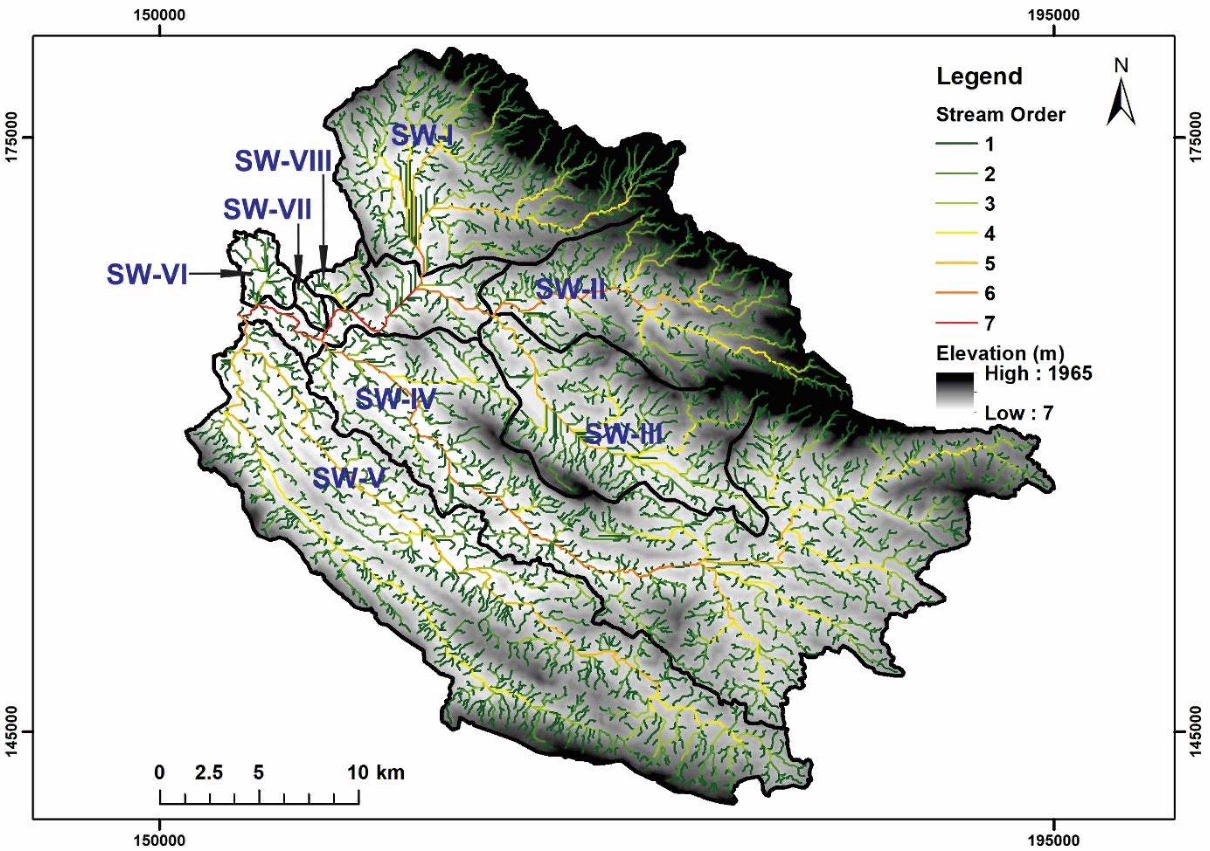

Fig. 3: *The DEM and the delineated drainage with stream orders*

Table 1: *Measured Linear, Areal, and Relief Morphometric Parameters*

#	Parameters	Formulae	Description	References
Linear parameters				
1	Stream order (U)	Hierarchical rank	The smallest permanent streams are called ‘‘first order’’. Two first-order streams join to form a larger, second-order stream; two second-order streams join to form a third-order, and so on. Smaller streams entering a higher-ordered stream do not change their order number	Strahler (1964)
2	Stream length (Lu)	Length of the stream	The total length of streams of each of the different orders in a drainage basin tends closely to approximate a direct geometric ratio	Horton (1945)
3	Bifurcation ratio (R_b)	—	The ratio of the number of streams of a given order (Nu) to the number of segments of the higher-order (Nu + 1) is termed as the R_b	Strahler (1964)
Areal parameters				
4	Drainage density (D_d)	—	The length of stream channel per unit area of a drainage basin	Horton (1945)
5	Stream frequency (F_s)	—	The ratio between the total number of streams and the area of the basin	Horton (1945)
6	Drainage texture (T)	—	the ratio between total numbers of stream segments of all orders to the perimeter of the basin	Horton (1945)
7	Elongation ratio (R_e)	$- = 1.28\sqrt{-}$	The ratio between the diameter of a circle with the same area as that of the basin *(A)* and the maximum length *(L)* of the basin	Schumn (1956)
8	Form factor (F_f)	—	The ratio of the basin area to the square of the basin length	Horton (1945)
9	Texture ratio (R_t)		The ratio between the first-order streams and perimeter of the basin	Schumm (1956)
Relief parameters				
10	Relief	$R=$	The maximum vertical distance between the lowest and the highest points of a basin	Hadley and Schumm (1961)
11	Basin relief (B_h)	B min	The maximum vertical distance between the lowest and the highest points of a sub-basin	Ozdemir and Bird (2009)
12	Ruggedness number (R_n)	R d	The product of the basin relief and its drainage density	Ozdemir and Bird (2009)

3.2.3 Relief parameters

Relief morphometric parameters, namely, Relief, Basin relief (B_h), Ruggedness number (R_n) were computed.

3.3 Surface Roughness Analysis

The soil surface roughness is a most commonly used indicator to describe the configuration of soil surface microrelief (García Moreno et al., 2011) which is known to influence many processes occurring on the soil surface, including runoff, soil loss and deposition (Jester and Klik, 2005; Darby et al., 2010; Rai et al., 2010; Vermang et al., 2013). Therefore, the alluvial deposits in the *Kalu ganga* basin are associated with quaternary alluvial fan (Deraniyagala, 1956; Gunatilaka and Almond, 2001; Manamendra-Arachchi, 2005) can also be traced through it.

The slope map of the study basin was obtained using the same ASTER GDEM with the resolution of a 30 m × 30 m cell and reclassified to 1^o intervals. Then, it was smoothed by the Focal Statistics Spatial Analyst tools in ArcGIS, the size of the area of 90 m × 90 m cell (Popit and Verbovsek, 2013) through calculating the variety (the number of unique values) of the cells in the neighborhood to obtain the surface roughness index of the study basin. Based on the roughness index, surface roughness map was generated and stretched between the lowest and the highest index values to differentiate smooth and rough surfaces. Then it was used to discriminate smooth alluvial plains.

4. RESULTS AND DISCUSSION

According to the delineated drainage network (Fig. 3), the sub-watersheds SW-V and lower part of SW-IV are characterized by a trellis drainage pattern. Probably, the drainage network follows the rectangular joint patterns (Kudahetty and Gunathilaka, 2004), faults, and fracture system of the basement hard rock. These features can be noticed in 1:100,000 geological map sheets (16, 17, and 20) published by GSMB of Sri Lanka. The rest of the study basin is predominated by a dendritic drainage pattern.

In general, the total length of stream segments is highest in first-order streams, and it decreases as the order increases, except on few occasions in sub-watersheds. These few exceptions (Table 2) may be due to the structural complexities in the basement hard rock particularly in such areas (Sameera and Perera, 2015; Kehelpannala, 2003).

4.1 Understanding of surface runoff and erosion

According to the results, the higher drainage density (D_d) value of SW-I (2.71) and SW-VI (2.68) indicate that the surface runoffs of these two sub-watersheds are higher than that of other sub-watersheds (Table 3). In addition to that, the basin relief (B_h) is directly related with discharge rate, denudation, and amount of sediment transport as described by Prabhakaran and Raj (2018), Ozdemir and Bird (2009), Schumm, (1956), Magesh et al. (2011), and Strahler (1964). SW-I has the highest basin relief (B_h) value (1.91), indicating that it has a much higher discharge rate, denudation, and amount of sediment transport than the other sub-watersheds. Furthermore, SW-IV (1.49) and SW-II (1.45) sub-watersheds have comparatively higher B_h values, indicating a relatively greater amount of sediment transportation.

The drainage texture (T) parameter values of SW-VI, SW-VII and SW-VIII show coarse drainage texture as per the classification introduced by Ali et al. (2018). This makes more prone to frequent flooding. In contrast, SW-I, SW-II, SW-IV, and SW-V show very fine drainage texture, indicating those sub-watersheds have much higher surface runoff with respect to others. The elongation ratio (R_e) parameter of sub-watershed SW-I (0.86) and SW-VI (0.85) indicate that they are nearly oval in shape (Schumn, 1956) and are more efficient in the discharge of runoff and show shorter times to peak than other sub-watersheds (Dar et al., 2013, Altaf et al., 2013, Bali et al., 2012). Form factor (F_f) is an index used to determine the shape of the basin (Horton 1945) and is an indicator of the flood formation and movement, degree of erosion, and sediment transport capacity in a watershed (Youssef et al., 2011; Howard, 1990; Kochel, 1988).

Table 2: *Linear morphometric parameters of the studied basin*

Sub-Watershed	No of Streams (Nu)							Total Stream No.	Basin Length (L) (km)
	1	2	3	4	5	6	7		
I	367	175	84	51	37	8	0	722	14.65
II	311	144	72	45	8	31	0	611	18.63
III	227	101	58	23	37	0	0	446	17.48
IV	870	406	203	132	28	82	0	1721	37.30
V	714	336	155	96	106	4	0	1411	36.76
VI	29	14	13	0	0	0	0	56	3.91
VII	7	6	0	0	0	0	0	13	2.92
VIII	21	8	10	2	0	0	0	41	3.73

Sub-Watershed	Stream Length (Lu)(km)							Total Stream Length (km)
	1	2	3	4	5	6	7	
I	187.13	78.72	37.52	21.56	16.27	1.89		343.09
II	112.88	63.43	30.84	16.89	3.49	9.99		237.52
III	109.04	50.44	20.30	13.09	11.25			204.12
IV	343.51	166.07	76.79	48.20	11.73	26.47		672.78
V	291.45	126.08	68.58	30.61	40.04	1.75		558.51
VI	14.18	5.61	3.24					23.03
VII	3.18	2.51						5.69
VIII	8.06	1.64	2.88	1.06				13.64

Sub-Watershed	Bifurcation ration (R_b)							Mean R_b
	R_b1	R_b2	R_b3	R_b4	R_b5	R_b6	R_b7	
I	2.38	2.10	1.74	1.00	11.42			3.73
II	1.78	2.06	1.83	4.85	0.35			2.17
III	2.16	2.48	1.55	1.16				1.84
IV	2.07	2.16	1.59	4.11	0.44			2.08
V	2.31	1.84	2.24	0.76	22.88			6.01
VI	2.53	1.73						2.13
VII	1.27							1.27
VIII	4.91	0.57	2.72					2.73

The ruggedness number (R_n) combines slope steepness and length to indicate the extent of land surface instability. It indicates the surface unevenness (Selvan et al., 2011; Soni, 2017) and erosion potential of the landforms (Rai et al., 2018; Vijith and Satheesh 2006). The highest R_n value of the SW-I (5.19) indicates its highest susceptibility for soil erosion (Altaf et al., 2013). The values of SW-II (3.45) and SW-IV (3.46) are also relatively high, indicating their comparative higher topographic effect on soil erosion than other sub-watersheds. The mean 'R_n' value of the study basin is 2.42 (Table 3). This higher mean 'R_n' of the basin suggests that the area may have intrinsic structural complexity in the basement rock in relation to relief and 'D_d'. On the other hand, the parameter stream frequency (F_s) relates to the permeability and infiltration capacity of a basin (Vijith and Satheesh, 2006; Montgomery and Dietrich, 1992; Horton, 1945). The relatively lowest F_s value of SW-III (5.29) indicates the higher infiltration capacity of its subsoil with respect to the other sub-watersheds. The rapid infiltration of rainfall, which causes soil saturation and a temporary rise in pore-water pressures, is generally assumed to be the mechanism by which most shallow debris landslides occur during high rainy seasons forming eluvial deposits in the basin. As infiltration is a complex process depending on the soil type, slope condition, and vegetation, this must be clearly confirmed by the field investigations.

Table 3 *Areal and Relief morphometric parameters of the studied basin*

Sub-Watershed	Areal Parameters								Relief Parameters			
	Area (A) (km^2)	Perimeter (P) (km)	Drainage density (D_d) (km/km^2)	Stream Frequency (F_s)	Drainage Texture (T)	Elongation Ratio (R_e)	Form Factor (F_f)	Texture ratio (R_t)	Elevation (km) Max	Elevation (km) Min	Basin Relif (B_h)	Ruggedness number (R_n)
I	126.11	54.16	2.72	5.73	13.33	0.86	0.59	6.78	1.97	0.06	1.91	5.19
II	99.66	50.98	2.38	6.13	11.98	0.60	0.29	6.10	1.52	0.07	1.45	3.45
III	84.36	49.60	2.42	5.29	8.99	0.59	0.28	4.58	1.21	0.07	1.14	2.77
IV	290.56	136.46	2.32	5.92	12.61	0.52	0.21	6.38	1.51	0.02	1.49	3.46
V	231.48	105.28	2.41	6.10	13.40	0.47	0.17	6.78	1.01	0.01	1.00	2.42
VI	8.61	14.87	2.68	6.51	3.77	0.85	0.56	1.95	0.17	0.02	0.15	0.41
VII	2.52	7.13	2.26	5.16	1.82	0.61	0.30	0.98	0.17	0.02	0.15	0.34
VIII	5.73	11.81	2.38	7.16	3.47	0.72	0.41	1.78	0.56	0.02	0.54	1.29

4.2 Understanding of sediment deposition

The parameter Bifurcation ratio (R_b) is a measure of the amount of branching in a stream network and it plays an important role in controlling the peakedness of the runoff hydrograph (Altaf et al., 2013; Schumm; 1956; Howard, 1990; Rakesh et al., 2000). The highest mean R_b value of the sub-watershed SW-V (6.01) (Table 2) indicates its early hydrological peak tending for flash floods. The outlet points of this sub-watershed experience frequent flash floods. The second largest mean R_b value of the sub-watershed SW-I (3.23) also indicate relatively higher flood vulnerability.

The surface roughness index calculation distinguished nine classes of surfaces in the study basin as shown in Fig. 4. Among them, the classes 1, 2 and 3 represent the smooth areas, class 9 represents the roughest areas, and the other classes (4-8) represent intermediate areas. This surface roughness map was cross-validated using known gem placers as shown in Fig. 5. It was noted that, 70% of known high potential alluvial gem occurrences are lying on the identified smooth surface areas. Therefore, it can be considered that this approach is good enough to locate possible alluvial deposits. The identified possible areas for alluvial deposits in the study basin are summarized in Table 4.

Table 4: *Calculated areas for possible alluvial deposits within sub-watersheds*

Sub-Watershed	Possible Areas for Alluvial Deposits	
	Area in hectare	Area percentage
I	709.65	5.6%
II	237.60	2.4%
III	798.39	9.5%
IV	1364.04	4.7%
V	1049.49	4.5%
VI	198.27	23.0%
VII	31.77	12.6%
VIII	28.80	5.0%

Despite the sub-watersheds VI and VII covering smaller areas, possible occurrences of alluvial deposits are high (Table 4). It may be due to the steep slopes in upper catchments meeting the flat areas (abrupt slope changes), and higher discharge of streams accumulate large volumes of water in the streams of lower elevated areas. Further, the coarse drainage texture is generally more prone to frequent floods (Ali et at., 2018). Even though the catchment areas of sub-watersheds IV and V are high, their percentage of possible areas for accumulation of alluvial deposits are low. That indicates more efficiency in the discharge of runoff in their low floodplain having fine drainage texture and trellis drainage pattern which provide rapid flow through the basin.

The identified other smooth areas (Fig. 5) are needed to be verified for the possibility of alluvial gem deposits through detailed field studies.

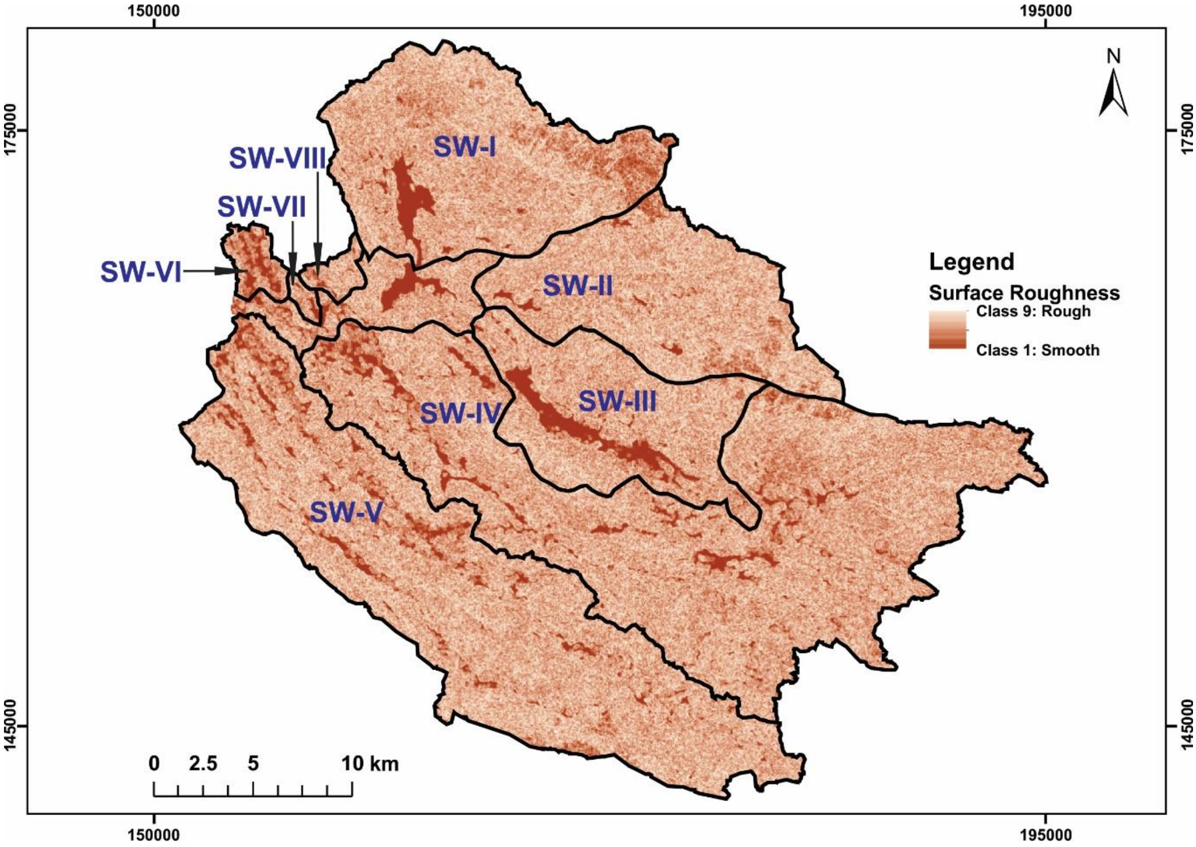

Fig. 4: *Extracted surface roughness map*

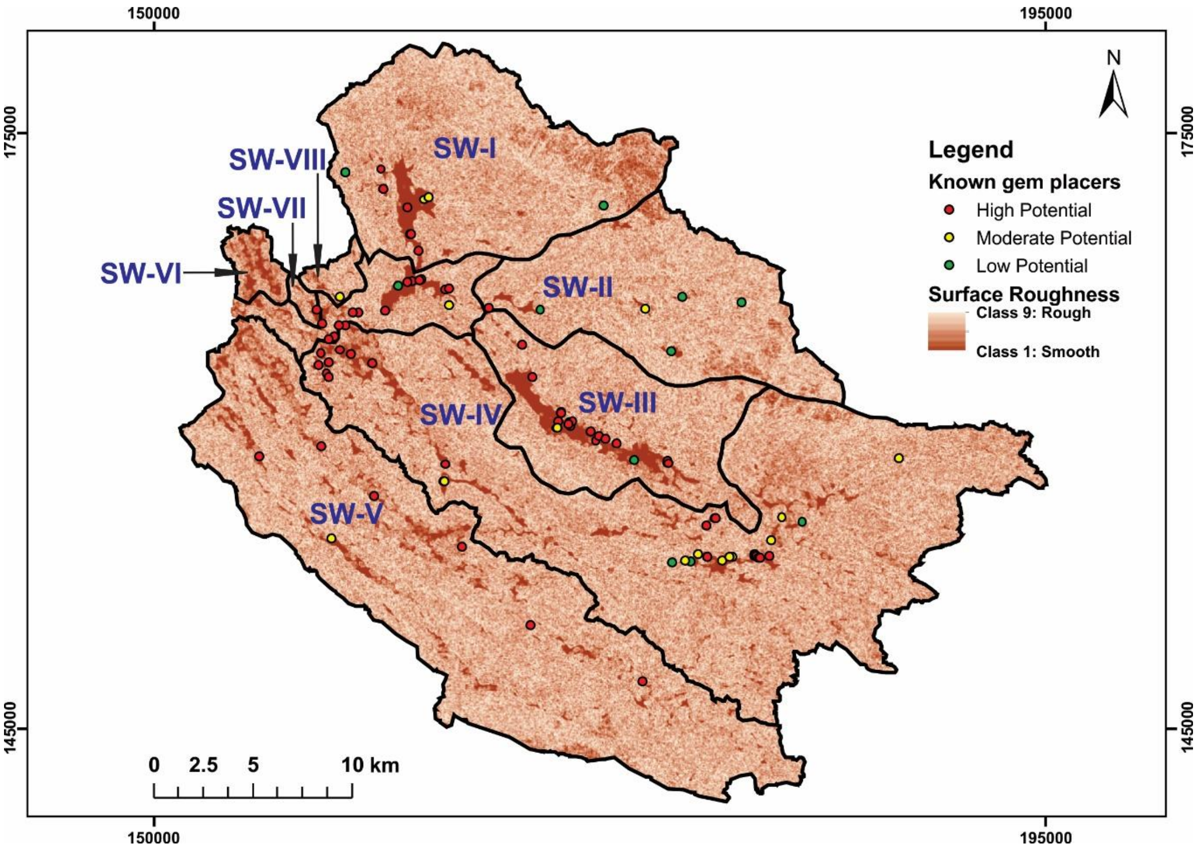

Fig. 5: *Surface roughness map cross-validated with known gem placers*

5. CONCLUSIONS

The morphometric analysis-based automated derivation of topographic watershed data using Digital Elevation Models with Geographical Information System techniques of the present study is critical for understanding hydrological behavior and the natural processes that result from it during the quaternary period. However, detailed studies on the paleoclimatic condition of the region are required in order to confirm the findings of the research. The generated surface roughness map is useful to predict the potential deposition of gem-bearing alluvial sediments. Several areas have been identified as having significant gem potential, and most of the known localities of alluvial gem deposits overlap with them. Since the factors of erosion, sediment transport and deposition, and surface roughness analysis have been considered for the morphometric analysis, gem potential alluvial deposits can be predicted with higher accuracy and at a lower cost.

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