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Importance of Drainage Density and Stream Network Ordering Schema of Drainage Basin; A micro catchment-based analysis

Ananda Y. Karunarathna
Department of Geography, University of Colombo, Sri Lanka

Correspondence: anandageocmb@gmail.com

Abstract

Protection of upper catchment areas has importantly been becoming challenged since the forest cover of upper catcment areas has been eroded dramatically for years. Especially, due to the expansion of antropogenic activities in the upper catchment areas in Sri Lanka, soil erosion, soil degradation, and soil loss have come to the fore. This circumstance directly affects the natural river systems. The key objective of this research was to analyze the drainage density and drainage richness of the Kukule upper catchment and its micro catchments. For the methodological approaches, this research considered the drainage density and the burfication ratio, in addition to the examining of river stream orders that invented by A. N. Strahler (A. N. Strahler's River Network Classification Law). The cartographic applications, such as the topological significance (e.g. elevations and water divides etc.) and mapping of catchment areas have prepared based upon the Geographical Information System environment. According to the results, the Kukule catchment identified as a rich catchment in drainage density and burficcation ratio. The Kukule catchment is identified as a fifth order river basin that consists of higher numbers of stream segments and nodes. This may because a part of the catchment belongs to the Sinharaja tropical evergreen forest reserve.

Keywords: Stream network ordering, Topological significant, Drainage density, Micro catchment, GIS.

1. Introduction and background

Upper catcment areas can be identified as the most sensitive areas of river systems of a country. This is because upper catchment area is the heart of the hydrological cycle (Strahler, 2013; Gabler, Petersen, Trapasso, and Sack, 2009). Protection of upper catchment areas has importantly been becoming challenged since the forest cover of upper catcment areas has been eroded dramatically for years. Especially, due to the expansion of anthrophogenic activities in the upper catchment areas in Sri Lanka, soil erosion, soil degradation, and soil loss have become key issues (Hewawasam, 2008; Karunarathne, 2009; Manawadu and Karunarathne, 2004). This circumstance directly affects the natural river systems (Nayakekorale,1998). Understanding of the exact situation of drainage densities of river systems of a country is more important especially for river basin conservation stretegies. On the other hand, this will be more worthwhile for upper catchment management planning as well. This is because this study will bridge the gaps of the existing body of literature, more significantly.

In general, watersheds (also known as driange basin or catchement) have different form of stream channels. Drainage basins consist of mainly main river(s) and their respective tributaries. In this sense the drainage area of streams are paramount important this is because the length of streams is determined by the extent of drainage areas (Gabler, Petersen, Trapasso, and Sack, 2009). Relatively large catchement areas consist of many sub-basins. All main and sub-basins generally consider as open systems since they have been involved with input (e.g. mainly precipitation) and output such as amount of water, sediment, and energy (Bunnet, 1973; Gregory and Walling, 1973). In some cases, the river considers as an energy system. Generally river energy has been used to transport sediments in a river system (Bunnet, 1973). Another important component of a watershed is the drainage divide. In Gabler, Petersen, Trapasso, and Sack's words, "the drainage divide represents the outside perimeter of a drainage basin and thus also the boundary between it and adjacent basins. The drainage divide follows the crest of the interfluve between two adjacent drainage basins. In some places, this crest is a definite ridge, but the higher land that constitutes the divide is not always ridge-shaped, nor is it necessarily much higher than the rest of the interfluve. Surface runoff generated on one side of the divide flows toward the channel in one drainage basin, while runoff on the other side travels in a very different direction toward the channel in the adjacent drainage basin" (see, Gabler, Petersen, Trapasso, and Sack, 2009). Kukule catchment also exemplifies the similar narratives that dividing its sub-basins into three parts by the definite ridges.

Drainage density is also considered as one of the components of a basin. According to the McGraw-Hill dictionary of earth sciences, "drainage density is the ratio of the total length of all channels in a drainage basin to the basin area" (Parker, 1997). Drainage density varies according to several basin-level factors, such as highly erodible and impermeable rocks (e.g. this tends to have higher drainage density than areas dominated by resistant or permeable rocks). In addition to that, the slope and vegetation cover is also dramatically affected by the drainage density of a catchment area (Gabler, Petersen, Trapasso, and Sack, 2009).

The method of River Network Ordering is one of the most important factors that classically used to determine the topological significance of a particular river network system. In Gregory and Walling's words, "Ordering is useful because it provides a rapid method of quantitatively designating any stream or stream segment around the world, but in each case, the segment method of ordering should be specified in conjunction method of ordering should be specified in conjunction with the scale of map used" (Gregory and Walling, 1973). In this context, several studies have been done on river network ordering to determine a sophisticated river network ordering system. The basic idea of stream order was introduced by R.E. Horton in 1945, famously known as "The law of Stream numbers". According to the concept of Horton, "the system consists in distinguishing among different classes of streams and in assigning to each stream of a certain class a given dimensionless number, in this fashion the label attached to each stream indicates the class which the stream under consideration belongs to, that is, its order". In Horton's system, he introduced channel segments were ordered numerically from a stream's headwaters to a point somewhere down stream. Numerical ordering begins with the tributaries at the stream's headwaters being assigned the value 1. A stream segment that resulted from the joining of two 1st order segments was given an order of 2. Two 2nd order streams formed a 3rd order stream, and so on. Analysis of this data revealed some interesting relationships. For example, the ratio between the number of stream segments in one order and the next, called the bifurcation ratio, was consistently around three (Pidwirny, 2006). However, some disparities can be identified from Horton's law. His stream orders might be influenced by the map scale and map quality. As instance, when map scale is smaller and maps are more generalized the first order tributaries could be disappeared.

Arthur Newell Strahler developed the "Strahler Stream Order**"** system in 1957 for classifying streams according to the power of their tributaries. This classification schema was developed based on Horton's law of river network and it was a modification of Horton's work. According to Stahler, when two 1st order streams come together, they become a 2nd order stream. When two second-order streams come together, they form a 3rd order stream (Figure, 01). If a 1st order stream joins a 2nd order stream, it remains a 2nd stream. Scheidegger (1968) noted that a characteristic feature of river networks is the approximate validity of Horton's law of stream numbers; the number of segments of a given order (Strahler) in a particular net forms an inverse geometric sequence. As same, Strahler (1957) noted that order is proportional to stream status as manifested in size of catchment, number and lengths of contributing streams, stream discharge, or channel dimensions. However, his system is simpler and more convenience to approach. Such a different river network classification method was developed by R.L. Shreve in 1969. Shreve noted that "... for a topologically random population of networks of given magnitude and order, the sets of stream numbers and their probabilities can be computed by means of the algorithm and formulas...." (Shreve, 1969). According to the Shreve's method, when two 1st order streams come together they become a 2nd order stream. If a 1st order stream joins with a 2nd order stream then it becomes a 3rd order stream. If a 2nd order stream joins with a 2nd order stream then it becomes a 4th order stream. The concept of equivalent integer or magnitude as pointed out also by Shreve, characterizes a network more precisely than stream order does. Furthermore, Milton, and Ollier, (1965), Cheidegger, (1968), have also introduced different river network classification systems. Milton and Ollier's method enables one to assign code numbers and letters to stream segments and junctions in such a fashion that each segment in the is given a unique label and on the other hand each stream segment in a given network has a unique label and this information is important in determining its relative locations. Cheidegger's Consistent stream labeling method neglects no junctions (Lewin, John 1970). In this context, this study applied the law of "Strahler Stream Order**"** in order to determine the narratives of the Kukule basin and its three sub-basins. More importantly, this study will bridge the gap of the extant body of literature of the river basin discourse of Sri Lanka, by examining the drainage density and the stream network orders of the Kukule basin.

2. Methodology

2.1 The Study Area

The study area is the Kukule Ganga watershed which is one of the main tributaries of the Kalu Ganga (Figure 2) in Sri Lanka. The Kukule Ganga begins from the Rakwana mountain range near Kalawana which is a major mid-basin tributary of the Kalu Ganga in the southwest of the island, 50 miles south of the capital city, Colombo. The total area of the Kukule catchment is 309.44 Square Kilometers and it is 12 percent of the Kalu Ganga catchment. The study area consists of three sub-catchments namely, Wewagama, Delgoda and Koswatte (Figure 1). Land areas and relative sizes of sub-catchments are given in table 1.

Table 1: Sub-catchments of the study area

Name of the sub-catchment	Area in Sq. km	%
Wewagama	69.55	22.476
Delgoda	106.76	34.501

Koswatte	111.40	36.001
Down valley area	21.73	7.022
Total	309.44	100.00

The Kukule dam site is next to the Sinharaja Forest Reserve which, due to its rich diversity of plant and animal life, is a UNESCO World Heritage site. The Kukule reservoir consists of 88 ha and water volume capacity is 1.6 million m3 (Feasibility study, 1992). Relatively Koswatte sub-catchment is the largest catchment while the Wewagama catchment is the smallest and Delgoda is the second largest sub-catchment of the study area (Table 01).

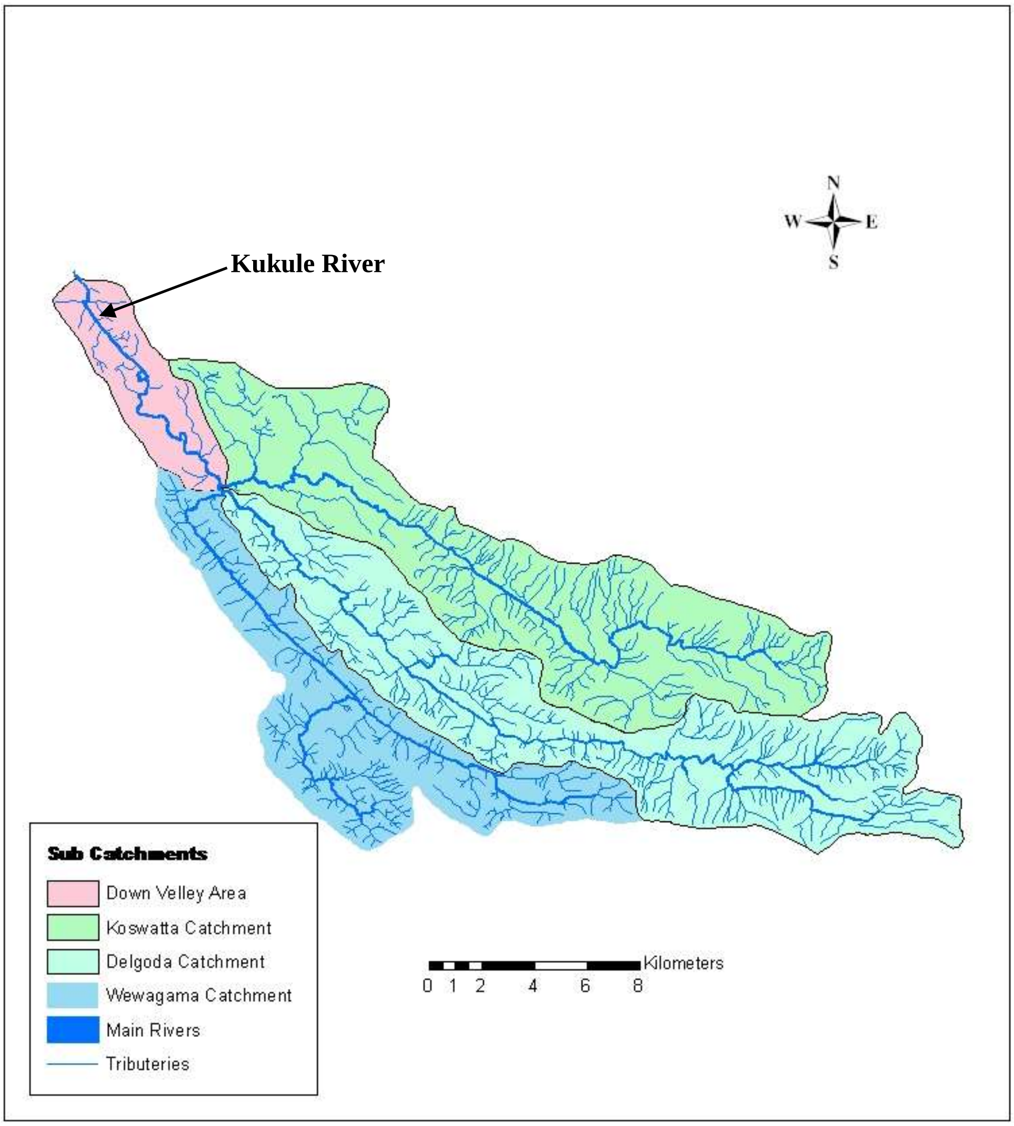

Figure 1: Sub Watersheds of the Study area
Source: Cartographic compilation by the Author, 2021.

Absolute and Relative Locations

The study area lies between 6^0 20' to 6^0 40' latitude and 80^0 15' and 80^0 40' longitude. The study area belongs to Rathnapura district (Figure 2) and consists of thirty Grama Niladari Divisions.

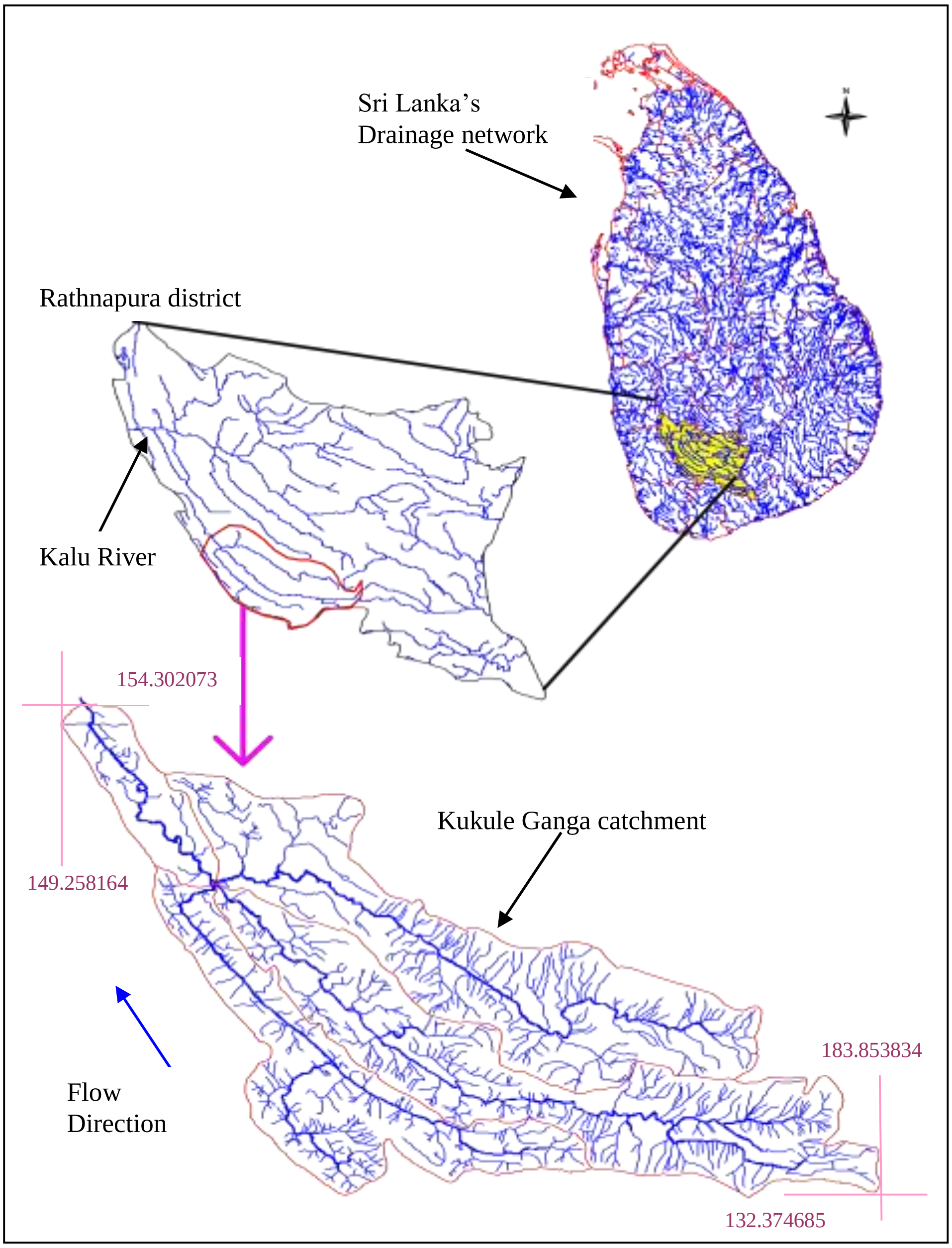

Figure 2: Relative and absolute location of the Study area

According to the calculated data, the total length of Kukule River is nearly 50 kilometers from Rakwana mountain range to Kukulegama area. Physiographically the study area belongs to the South – Western part of Sri Lanka. Kukule Ganga catchment area mainly consists of highly dissected ridges, steep slopes and isolated valleys. The catchment has divided in to the inter valleys at the altitude of 600 meters.

2.2 Key Methods

Each river system has an intrinsic hierarchical structure that can be described by different stream ordering procedures. This hierarchical structure can be utilized as the basis for a feature elimination procedure. Stream order is measure of the position of a stream in the hierarchy of tributaries. The criteria for stream order enumeration, though, may be geometric, topologic, or volumetric (Liu YAOLIN et al., 2002). The study used A.N. Strahler's river network classification schema (Figure 3) to analyze the Kukule river system as described in the previous section.

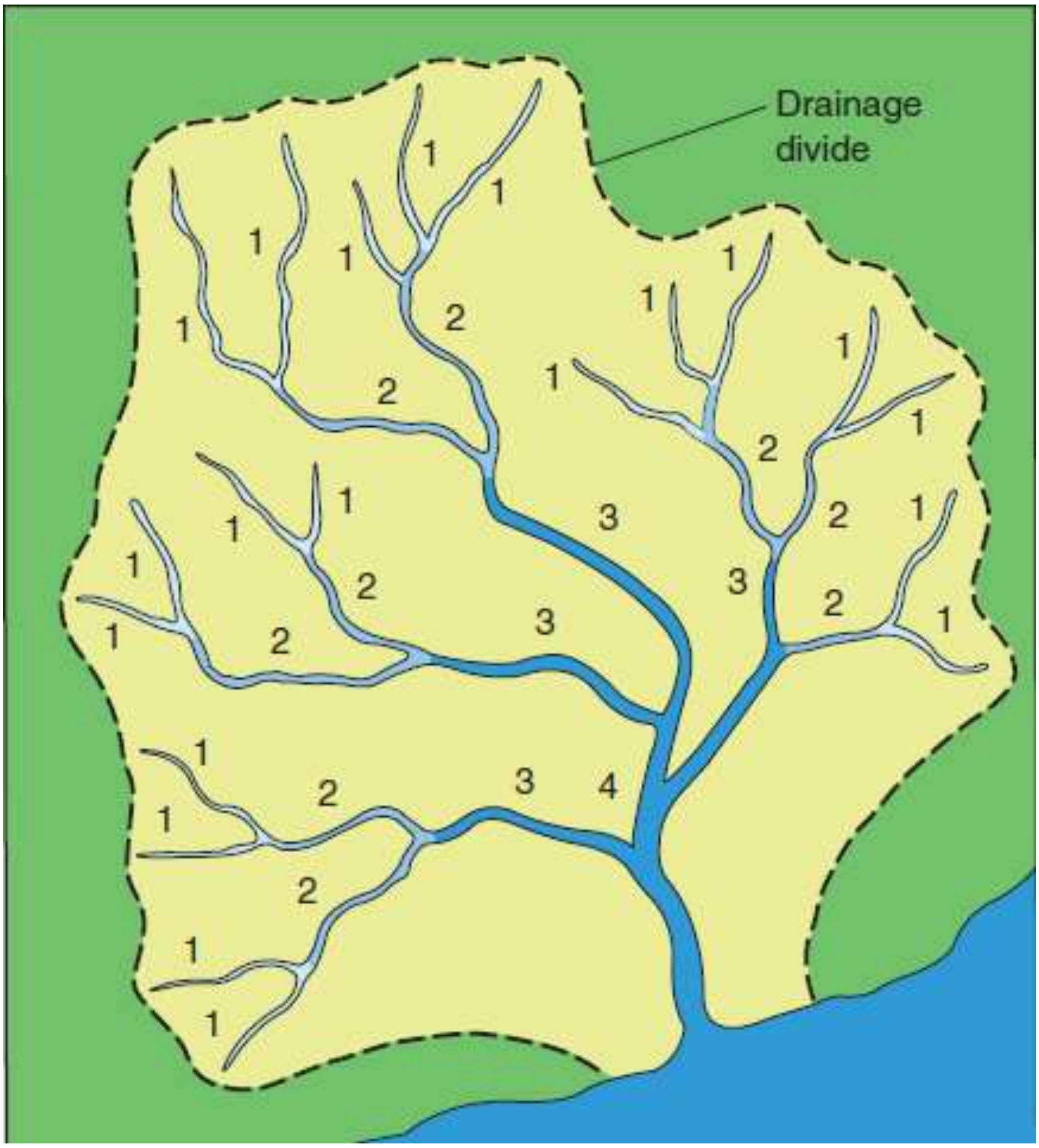

Figure 3: A. N. Strahler's River Network Classification System
Source: Gabler, Petersen, Trapasso, and Sack (2009).

According to figure no 3, the following understanding can be drawn;
1st order stream – un-branched, the lowest level of the catchment
2nd order stream - all tributaries are first order; combine with other 2nd order streams to form 3rd order
3rd order stream - should have two 2nd order streams and may also have 1st order
4th order stream - should have two 3rd order and may also have 1st and 2nd order

Strahler's system of stream orders, a lower order segment joins with a higher order segment as a hierarchical order (figure 3). According to the above methodology all the conditions were applied to the Kukule micro-catchment area in a GIS environment. Basically all the maps (Stream Network, Catchment boundary, sub-catchment areas, and contour/elevation) were scanned and digitized in a precise manner and converted to digital layers. Then build and joined attribute (aspatial) database to the spatial database. Finally, all the tributaries and rivers were labeled and classified according to the selected methodology.

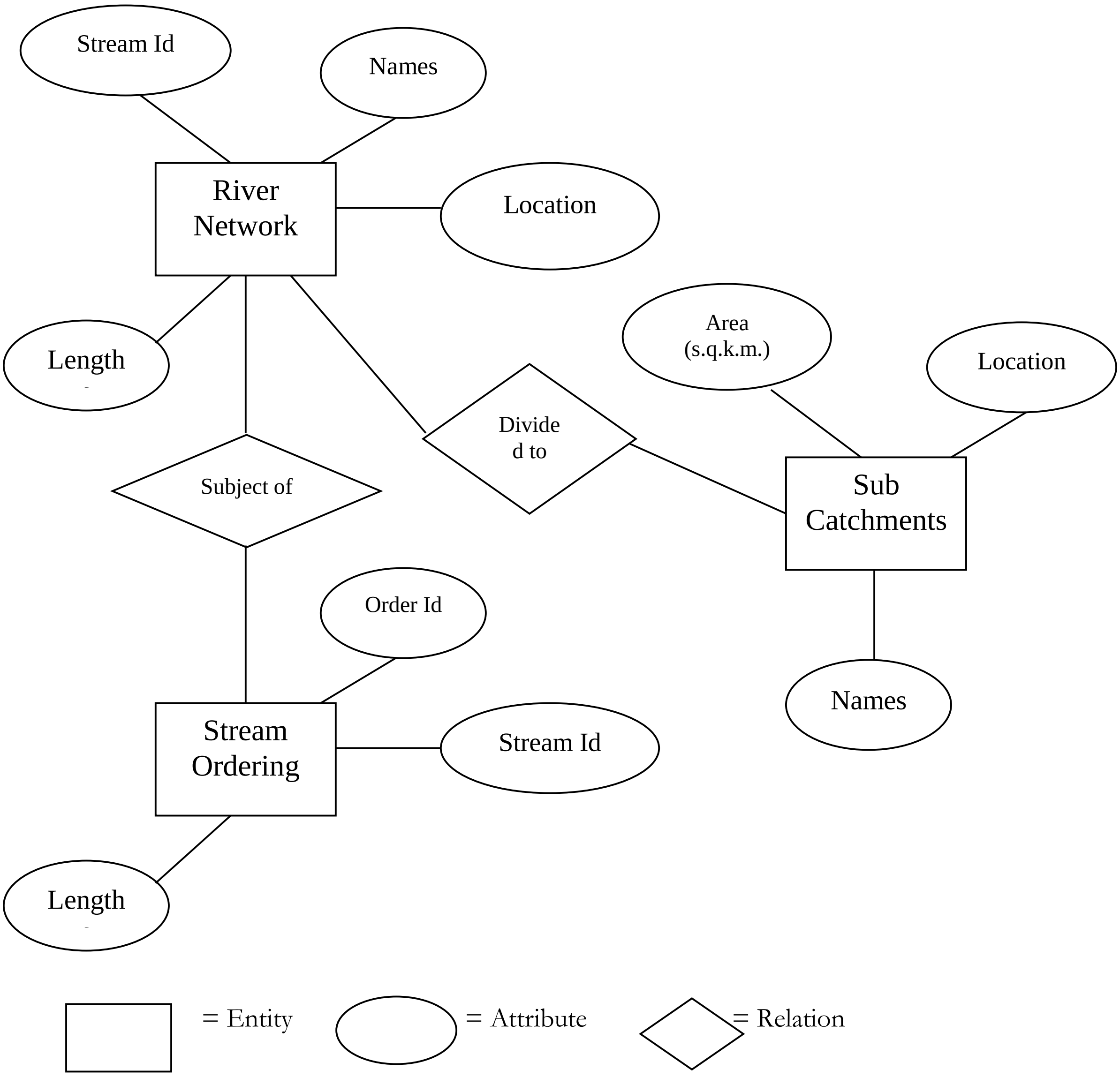

Figure 4: Conceptual relational Data Model for Classified Kukule River System

Figure 4 depicts the structure of spatial database and its characteristics and relations to each other. This structure was used to analyze and determine the classification method that was applied for the Kukule river system. The drainage density map (Figure 5) was created using the data derived from the stream orders (figure 6) of the catchment area. The Drainage density values were calculated according to the following formula (Gabler, Petersen, Trapasso, and Sack, 2009; Bunnet, 1973).

Drainage Density = Total lengths of streams / Total area of the basin **(1)**

The second drainage ratio, the Bifurcation ratio or the law stream numbers (see, Bunnet, 1973), was calculated using the stream network order values as shown in following table 2 and also by using the following formula (2).

Bifurcation Ration = steam segments of one order/ stream segments of next order **(2)**

3. Results and discussions

The results revealed that the drainage patterns of the main rivers and tributaries are dendritic and parallel (Figure 05).

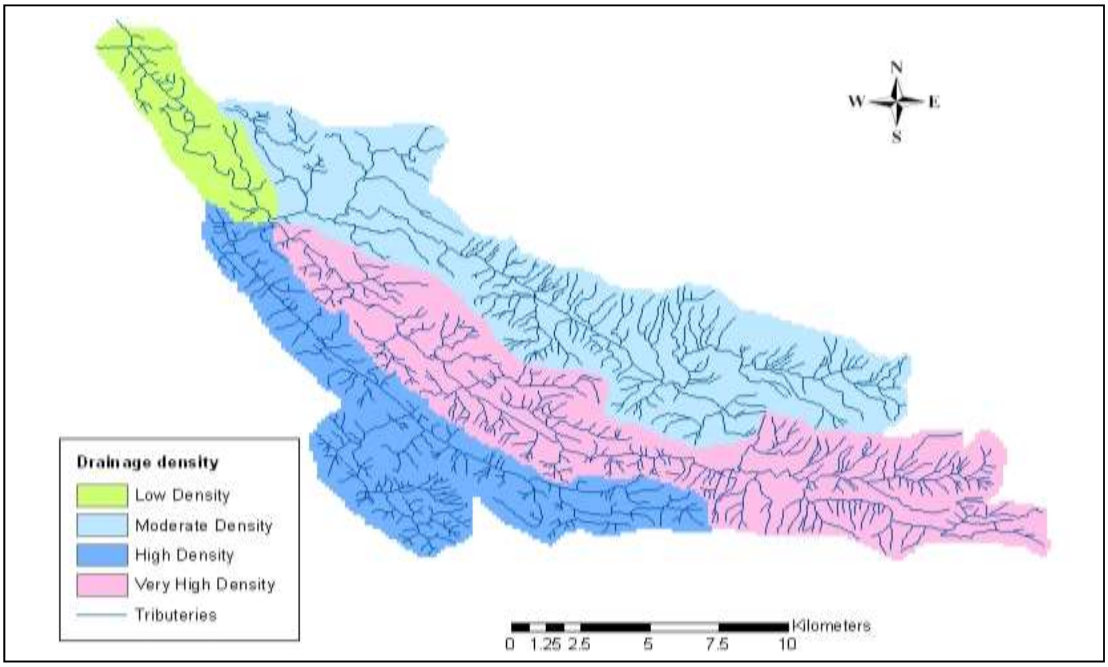

Figure 5: Distribution of drainage density of catchment area

According to the drainage density values, the catchment was classified into four density classes namely Low, Moderate, High and Very high drainage density areas (figure 05). Consistent with the calculated drainage density, Delgoda sub-watershed is the highest drainage density sub-basin area while the down valley is the lowest density area (Figure 05).

The study remarked that the 'high' drainage density is the Wewagama sub-catchment which belongs to the Sinharaja world heritage forest reserve and the 'moderate' density is the Koswatte sub-catchment area. The 'very high' density sub-basin is exemplified that the rich drainage watershed with more closely spaced and numerous sub-tributaries.

The classifications of the study were identified the five stream orders and 1260 segments (figure 6) The total length of streams is 694,220 meters among three sub-catchments of the study area. According to the analysis of tributaries, the highest order (5th order) is belongs to the sub-catchment of Wewagama and down valley area (table no 2). More importantly, Delgoda and Koswatte sub-catchments are belonging to the 4th order of classification. The Delgoda sub-catchment has the highest numbers of streams while Koswatte and Wewagama are respectively second and third.

Table 2: Drainage orders and lengths by Sub-watersheds (length in 000 meters)

Sub-catchment/ *Stream orders*	Delgoda		Wewaganga		Koswatta		Down valley	
	No. of stream	Length	No. of stream	Length	No. of stream	Length	No. of stream	Length
1st order	257	151.32	198	97.59	169	137.42	25	16.67
2nd order	128	56.34	102	28.79	90	49.44	7	5.32
3rd order	79	28.32	38	15.79	49	25.83	-	-
4th order	53	27.37	20	12.11	33	18.5	1	0.2
5th order	-	-	**1**	10.98	-	-	**1**	12.98
Total	517	263.35	368	165.26	341	231.19	34	35.17

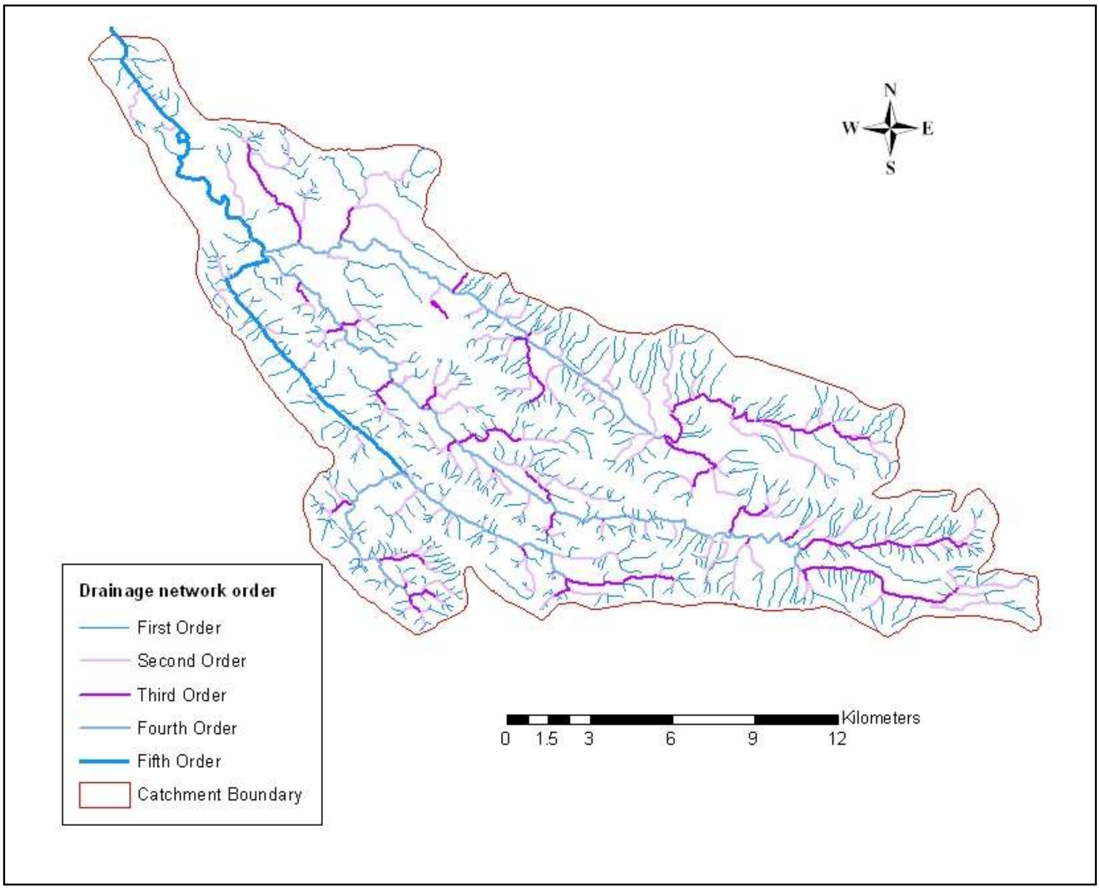

Figure 6: Ordered drainage network of the study area.

Delgoda sub-catchment consists of 257 1st order tributaries while the rest (Wewagama and Koswatte) are consisting of 198 and 169 tributaries respectively.

The second, third and fourth orders are predominant in the sub-catchment of Delgoda. These values are indicated that the importance of topological significance of study area. More importantly, the highest drainage density and the highest records of tributaries are observed very close proximity areas to the dense forest covers.

Figure 7: Dense forest near the upper part of Kukule basin

Figure 7 exemplifies that the dense forest and vegetation cover has been mattered to shape the number of tributaries, their stream orders and the drainage richness, as what Gabler, Petersen, Trapasso, and Sack (2009) are explained.

The analyses ware revealed that there is a significant relationship between stream orders and the number of tributaries as described by Strahler 1957 (figure 8). Furthermore, the identified relationship can be seen through sub-catchments of the study area (figure 9).

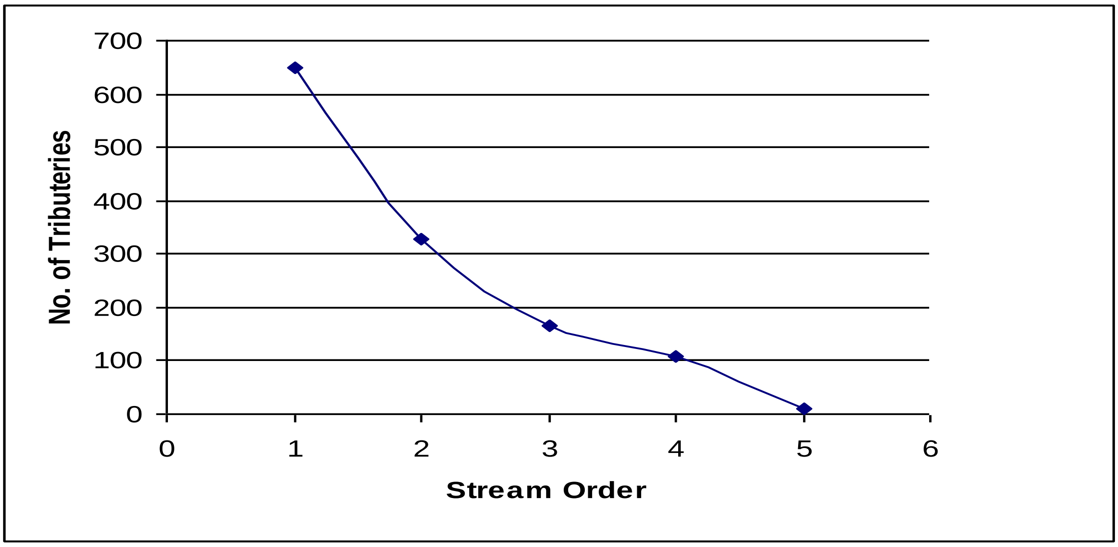

Figure 8: The relationship between stream order and tributaries

Table 3: Calculation of Bifurcation ratio

Stream Order	No of Segments	Bifurcation Ratio
1st Order	649	1.99
2nd Order	327	2.11
3rd Order	156	1.27
4th Order	123	2.37
5th Order	52	

The law of stream lengths expresses the average length of streams of a given order in terms of stream order, average length of streams of the 1st order, and the stream-length ratio. This law takes the form of a direct geometric series. These two laws extend Playfair's law and give it a quantitative meaning (see, Horton, 1945).

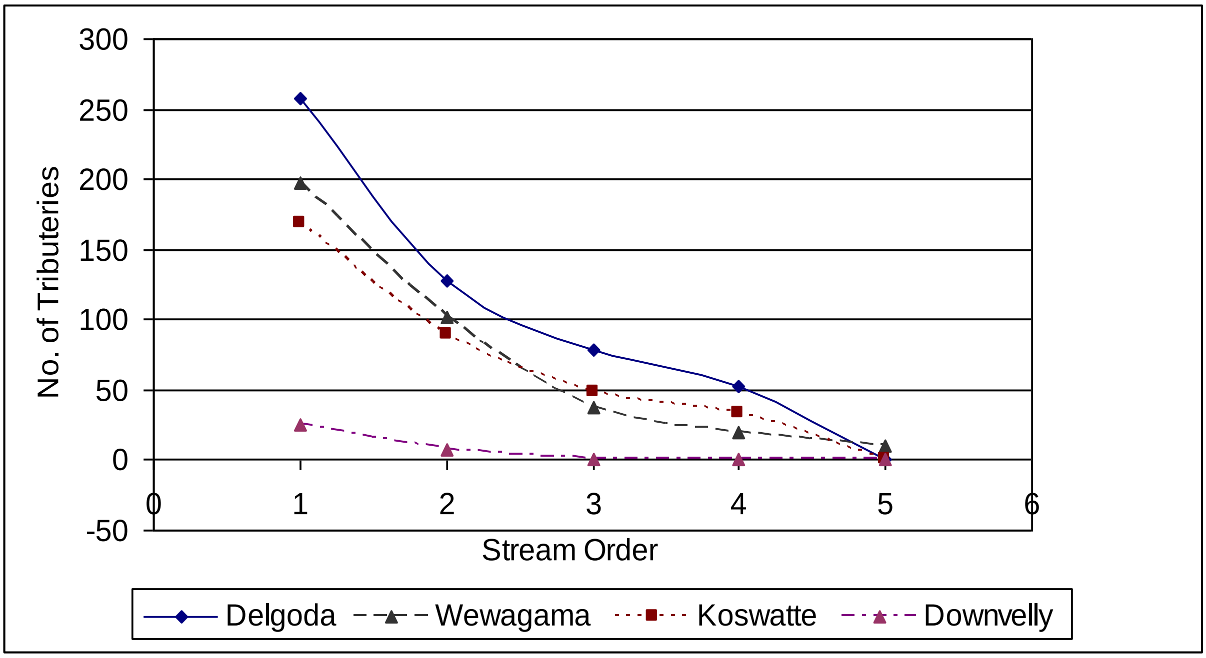

Figure 9: The association between stream order and tributaries of sub-catchment areas.

According to the figures and calculation of Bifurcation ratio (table 3), first order streams might be drain 50 percent of area of Kukule catchment as it is a high order drainage basin. The dispersion of stream orders is high among down valley area and other sub-catchments due to fewer amounts of streams segments in the down valley area (figure 9). However, Strahler's classification system represents general information of river system as well as stream order numbers and level of tributaries regarding of topological significance. One of the key dilemmas in upper catchment areas of Sri Lanka is the rapid changes of land use and land covers due to the meteoric rise of the anthropogenic activities (see, Karunarathe and Lee, 2019). Basically, this situation can be understood by considering the existing global impasses of deforestation and the escalation of global warning. Especially, many areas of throughout the world have been experienced forest fires, global warming, and unexpected climatic change related calamities (see, Mailman, 2021; Milhorance, 2021; Helmore, 2021; Watts, 2021). This adverse situation can be aligned with the Sri Lankan situation as well. In particular, the upper catchment areas of Kukule catchment have been experienced the similar narratives. Due to Chena cultivation, burned lands tend to be eroded by the rain splash and overland flow dramatically. Especially, the Chena cultivation areas are more vulnerable erosion potential areas. Moreover, a range of deforestation practices can be observed in the upper basin areas (see, figure 10 and 11). According to the figure 10 and 11, all the deforested patches are belong to dense forest areas. The forest cover acts as a protective layer or buffer on ground surface. Therefore, when forest cover removed from the topsoil the land significantly experiences for the excessive erosion.

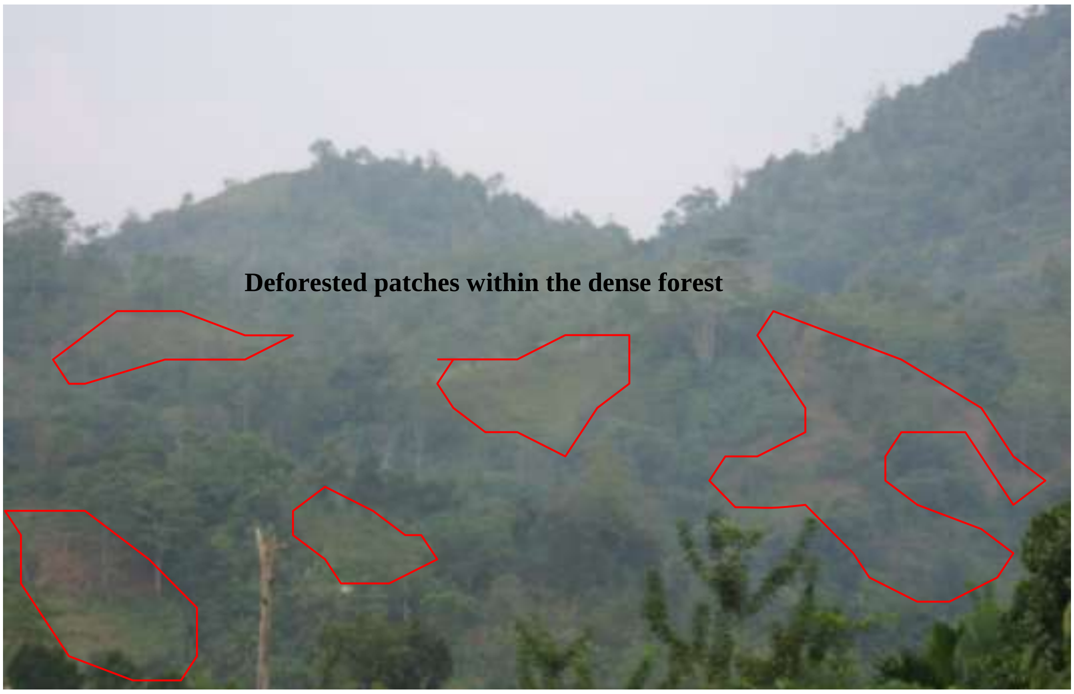

Figure 10: Deforestation for Chena cultivation in Kukule upper basin area.

Figure 11: Deforestation for Chena cultivation in Kukule upper basin area.

Particularly, Grama Niladari Divisions (GNDs) such as Gangalagamuwa, Panapola, Rambuka, Weddagala east, Jathuwangoda, Meepagama and Koswatta which are located upper catchment areas are more critical due to the rapid expansion of anthropogenic activities. This is because, it is paramount important to take necessary actions to control deforestation and sophisticated strategies are needed to be initiated at the immediate manner. On the other hand, these practices will be helped to accelerate the climatic changes and related impasses. When the cascading disasters are unfolded and experienced like Covid 19 plus other climatic calamities, the livelihoods of communities will be highly affected. Therefore, taking right actions for protecting of upper catchment areas and their rich natural characteristics have been come to the fore.

4. Concluding Remarks

According to the revealed results, the Kukule catchment can be identified as a rich basin following its natural characteristics such as drainage density and river network orders. More importantly, Delgoda, Wewagama, and Koswatta Sub-basins were identified as naturally rich drainage basins with high drainage densities respectively. The results also revealed that significant associations between the number of tributaries and stream orders. It is also observed that a very high number of tributaries are belonging to the Kukule catchment area exemplifying that the basin is located in the Wet zone area of the country. In other words, the study traced that the Kukule River System is a fifth order river system that represents high topological significance with enormous numbers of rich tributaries. Despite this study demonstrates that the Kukule catchment is a natural basin with very rich drainage characteristics, the upper catchment areas have been exemplified dramatic deforestation cum heighten anthropogenic activities. The future research foci will be touched the deforestation practices of upper catchment areas in order to protect their rich natural characteristics. It also helps to reduce the cascade disaster events. The Covid 19 pandemic situation has also been interlaced with some of hydrometeorological calamities. Therefore, the implication of this research will be significant and this also will contribute to protect upper catchment areas of the country.

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