Impact of Tectonic Uplift in Paro Chu Basin, Bhutan

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Abstract

The Paro Chu, originating in the southern slope of the Jomolhari Peak of the Bhutan Himalaya, is a right-bank tributary of the Wong Chu. It passes through a wide variety of rock beds, which have differential status of metamorphism. The drainage basin shows the impact of variable rock characteristics and tectonic movements on stream network, valley-form and channel morphology. Morphometric studies of stream networks with testing of Horton's Laws of stream number and stream length have revealed the deviation of streams from the Laws in relation to litho-characteristics and tectonic influences. The Asymmetry factor (AF) and Transverse topographic symmetry factor (TTSF) also indicate the tilting of the basin landscape. The valley-form significantly changes in different reaches of the Paro Chu. After the initial gorge segment, the course of the channel drains through a flat floodplain at Paro Town and beyond, but the lower course again passes through a narrow and deep gorge right up to the confluence. The stream gradient changes distinctly in the three valley forms. The braided reaches of the stream mark the impact of structural dismemberments under tectonic influence and the carrying of excessive quantity of sediments as related to the shearing of rocks in the immediate upstream of the braided parts. The variation of hypsometric integrals clearly reveals differential erosion under the impact of tectonic uplift and variable resistances of the rocks composing the drainage basin.

Keywords: Paro Chu, Stream Network, Horton's Laws, Metamorphism, Tectonic uplift, Valley-form, Braided part, Hypsometry.

1. Introduction

The Paro Chu originates from a glacial field of the Bhutan Himalaya on the southern slope of the Jomolhari Peak (7314.29 m or 23997ft) at about 5496.40 m (27°46´ N/89°14´ E) of elevation. The stream has passed through Paro town. Finally, it drains into the Wong Chu as a right-bank tributary (Fig. 1). The elevation at this point is about 2103.12 m approx. (Plate 1). Thus, the stream crosses about 3393.28m (11100ft) of relief. The Paro Basin, covering 1231.4 km^2, is elongated in shape, having distinct changes in the cross profiles of the valley.

Fluvial erosional landscape is highly sensitive to tectonic uplifts (Holbrook, et al., 1999). A competition for channel adjustment between the rate of uplift and the rate of downcutting immediately starts in order to maintain a steady state. Eventually, a disequilibrium between the erosional process and local elevation may develop with time, depending on the erosion and transportation efficiency of the channel (Whipple, K. X. et al., 1999); (Willett, S. D. et al., 2001); (Bonnet, S. et al., 2003); (Whipple, K. X. et al., 2004); (Whipple, K. X. et al., 2006); (Simoes, M. et al., 2010).

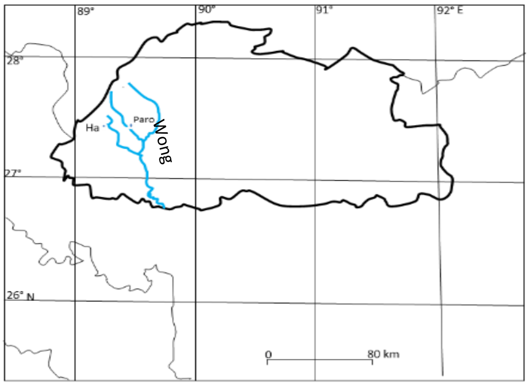


Figure 1: Location of Paro Chu

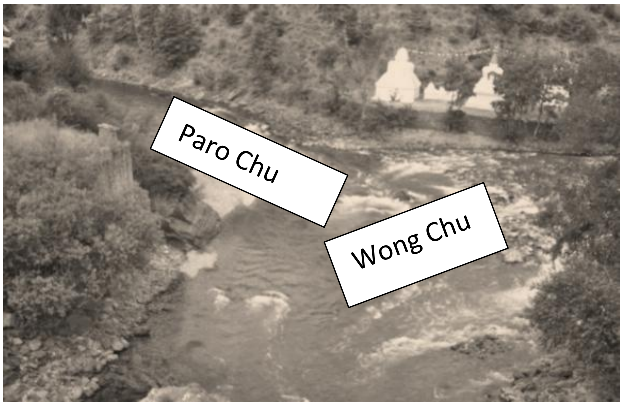


Plate 1: Confluence of Paro at Chhuzom
(Photograph by author)

The terrain of the Himalayas has been rising very slowly on account of the under thrusting of the Indian plate beneath the Himalayan mountains, more or less, at a rate of 7±2 mm per year in the Great Himalayan region (Valdiya, K. S., 2004). The Paro basin in the Bhutan Himalaya, located in the north of the Main Central Thrust (MCT), is prone to the impact of such tectonic disturbances, and the topographic signatures of such impacts are well exhibited in this small basin. The major discrepancy noted is the disequilibrium between the altitude and local relief of the basin. Chhuzom, or the confluence of the Paro Chu with the Wong Chu, has a much higher relief than that of Paro town, which is located far upstream at a much higher altitude.

A thorough survey of published literature shows the trend of incision at the face of the uplift of the terrain. It indicates the presence of high altitude-low relief with low gradient and downstream steepness in the mid-latitude region of the Bhutan Himalaya (Duncan, C. et al., 2003). They ascribe this to the infilling of previously carved 'V-shaped valleys. Adams et al. (2016) consider this high elevation-low relief phenomenon of Bhutan as the impact of tectonic activities. Simoes et al. (2021) have similar observations on some other rivers of Bhutan, namely, the Amo Chhu, the Wang Chhu, the Puna Tsang Chhu, the Mangde Chhu, the Chamkhar Chhu, the Kuri Chhu, and the Dangme Chhu. They have mentioned the steep downstream profiles of those streams below Knick points, with their upstream reaches having low relief either on account of local alluvial fill of previously incised valleys in situ, or are uplifted relict landscapes. However, none of them has discussed the disequilibrium in the topography of the Paro Valley, though during the field studies, the present author has come across the same discrepancy.

This paper explains the high altitude - low relief in the upstream segment and low altitude - high relief in the downstream segment as a disequilibrium in the Paro valley. The morphological changes of the Paro Chu have also been examined in that respect. Furthermore, the stream network deviates from Horton's Laws of stream number and stream length. This has been explained in terms of lithological resistances.

2. Materials

The litho-characteristics of the basin have been identified based on studies done by previous researchers, as appeared in the published literature. Some megascopic examination of the rocks in the field, especially in the valley-walls of the Paro Valley, has been accomplished. The network of streams in the basin has been identified from USGS topographic sheets and SRTM DEM (30 m resolution). The DEM is also used to prepare the slope map and hypsometric curve of the Paro Chu basin. The field visit to the Paro Chu basin also includes examining a braided part of the channel. However, the braiding index was determined using Google Earth Pro images. Photographs of the features of the Paro Chu basin are taken in the field by the author himself.

3. Methods

This research has been accomplished through a combination of field study, study of topographic sheets, and use of geospatial techniques. The field work was done in 2015 throughout the accessible part of the Paro valley. Topographic sheets have been used in the construction of longitudinal and transverse profiles of the valley along with the determination of spot heights, and determining the gradient of slope of the Paro valley. The randomness of the network of streams has been examined by Shreve's binary notation (Shreve, 1966) of interior and exterior links. The morphometric study of the Paro basin has been done adopting various methods (Table1) suggested by Horton (Horton, 1945), Miller (Miller, 1953), and Schumm (Schumm, 1956).

Table 1: Formulae used in morphometric analysis

Drainage density	Σ Cl/A	Horton (1945)
Bifurcation Ratio	N_u/N_{u+1}	Horton (1945)
Length Ratio	L_u/L_{u-1}	Horton (1945)
Circularity ratio	$4\pi A/P^2$	Miller (1953)
Elongation ratio	$2\sqrt{A/\pi}/L$	Schumm (1956)
Law of Stream number	$N_u = r_b^{(k-u)}$	Horton (1945)
Law of Stream length	$Lu = l_1 r_l^{(u-1)}$	Horton (1945)

3.1 Basin asymmetry factor

The impact of tectonic tilting has been examined by Asymmetry Factor (Hare, P. H. et al., 1985), The formula used to determine this factor is

$$AF = 100.\ A_r/A_t \quad (1)$$

[Ar = Area in the right bank of the stream; At =Total area of basin]

3.2 Transverse topographic symmetry factor (TTSF)

Transverse Topographic Symmetry Factor (Cox, R. T., 1994), being the ratio between the distance of the mid-line of the basin from the main channel and from the water-divide, is a measure for the understanding of the tectonic impact on basin topography. The formula used is,

TTSF = Da/Dd (2)

[Da = Distance from the midline to drainage axis; Dd = Distance from the midline to water divide].

Braiding index (BI) has been determined by Brice's method (Brice, 1964).

BI = 2Σ Length of bars/Length of reach (3)

The map of distribution of the amount of slope has been prepared through ArcMap 10.8.

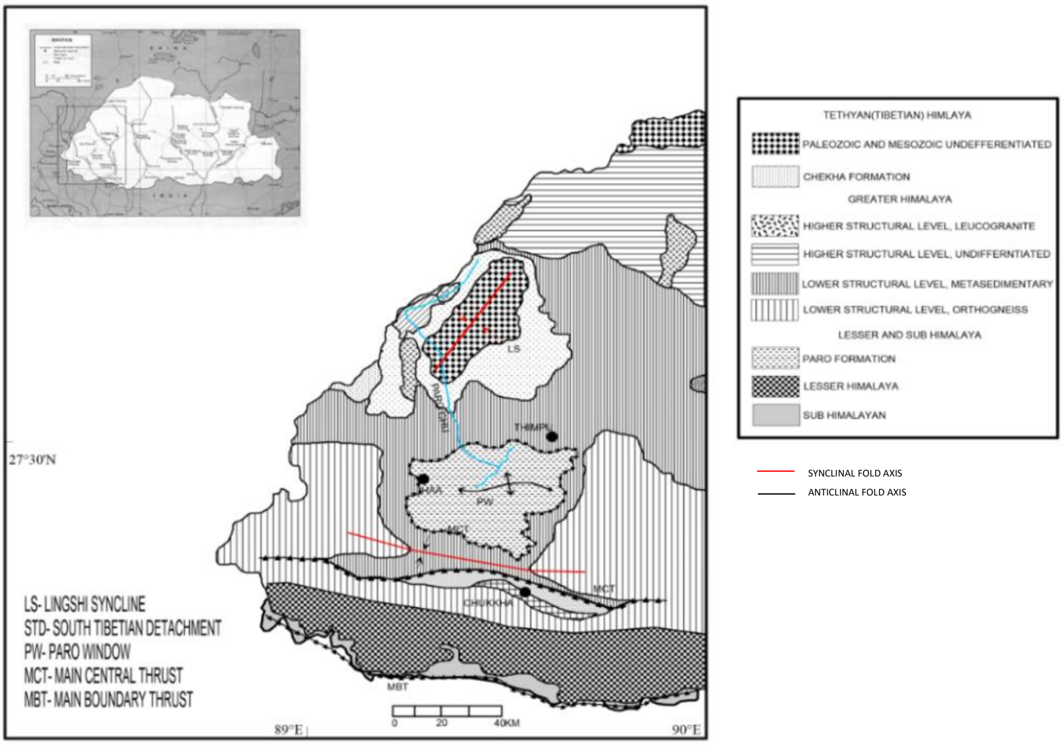


Figure 2: Generalized Geological Map of the study area
(Source: modified from Long, Tobgay *et al.*)

4. General geology of Paro basin

Bedrock channels are often controlled by litho-characteristics in their planform and flow direction depending on their variable resistances and structural attitudes, such as dip, strike, litho-contact, etc. (Charlton, 2008). (Long et al., 2011) studied the detailed geology of the Bhutan Himalaya, where they showed that the Paro Chu rises from the Chekha formation of the Tethyan Himalayan exposures composed of quartzite inter-bedded with biotite–muscovite–garnet schist belonging to the Ordovician deposits (Fig. 2). Then it crosses some meta-sedimentary rock-beds of the Greater Himalaya belonging to the South Tibetan detachment and across the Lingshi syncline, it passes through the Chekha formation first and then through the meta-sedimentary rocks consisting of quartzite, schist and para-gneiss of lower structural level than the Greater Himalaya. However, the meta-sedimentary rocks are weaker in resistance capacity to erosion as they comprise rocks of lower-grade metamorphism. Finally, the channel enters the 'Paro Window' north of the Paro Dzong. Near Chhuzom, some small sheared recumbent folds (Plate 2) have been marked in the valley wall. The axes of these small folds are ruptured, marking the structural disturbance.

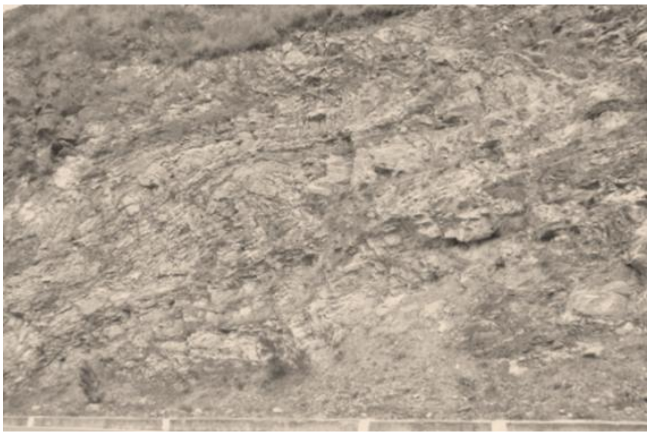


Plate 2: Ruptured recumbent folds on valley wall at Chhuzom
(Photograph by author)

The Paro Formation generally refers to the group of rocks present in Paro, Haa, Bunakha, and Thimphu areas. A simple description of the composition of the Paro Formation includes high-grade metasedimentary and calcareous rocks and some calc-silicate rocks. The particular rock types identified are marble, quartzite, quarts-garnet-staurolite-kyanite schist, some subordinate feldspathic schists, and orthogneiss having mica granite composition (Dasgupta, 1995b) (Gansser, 1983). The Paro Formation occurs as an anticlinal ridge, though the Paro Chu and Wong Chu incisions have dissected it. As suggested by Tobgay *et al.*(Tobgay, 2012), it comprises accumulated sediments from 'heterogenous' sources as controlled by tectonic activities. The input of sediments varies in accumulation rate (DeGraaff-Surpless et al., 2003). Long *et al.* (Long et al., 2011) further suggest that the litho-characteristics of the Paro Formation indicate those to be similar in deformation to that of the Greater Himalayan rocks, though they have a Lesser Himalayan provenance (Tobgay, 2012). The tectonic identity of the Paro Formation is still uncertain. Geologists have opined differently regarding the affinity of this formation. Considering the litho-characteristics and lower-grade metamorphism, Jangpangi (Jangpangi, 1978, 1980) correlates the upper quartzite-rich section with the Shumar and the lower carbonaceous section with the Buxa Formation of the Lesser Himalaya. Gansser (1983) considers the upper greenschist of the Paro Formation to be the amphibolite facies and has included those in the map unit of the Greater Himalaya sequence. The lack of fossil records and no scope radiometric dating have insisted on isotope geochemistry and field observations to determine the stratigraphic order of the Lesser Himalayan rocks of Bhutan Himalaya (Bhargava, 1995); Gansser, 1983).

5. Randomness of network

To check whether the network is topologically random or not (Shreve, 1966), the method of binary notation is followed. It gives the number of exterior links or source links to be 141, whereas the interior links or joiner links are 117. Hence, it indicates a lack of topological randomness in the stream network., which indicates structural and lithological control over the stream network. The binary string of exterior and interior links is given below.
01001010101001101101100110001010110110110011001001001111010001100110011001010110100010110001010001100010101011110011011100001000011010011111010001110111100110100001111110111001111101110010100110011100010101101100111101010011111110110001111011001011001101111= (0 =117) (1=141)

6. Morphometric Study of Network

The morphometric characteristics of the stream network of the Paro basin (Fig. 3) have been compiled in Table 2 and Table 3, the former being related to the observed values and the latter is related to calculated values following Horton's laws of stream number and stream length. Stream initiation, however, is not uniform over the entire basin. The network is more elaborate towards the left bank than the right bank.

In Table 3, the calculated values of stream numbers and mean stream length have been computed. These estimated values are obtained on the basis of Horton's law of stream number ($N_u = r_b^{(k-u)}$) and law of stream length ($Lu = l_1 r_l^{(u-1)}$). When the calculated values as well as observed values are plotted on a semi-log graph, the trend of geometric series for observed values in both cases is well marked, though the values (Table 4) deviate from the estimated ones.

As revealed in Table 2, the Paro Chu is a fifth-order channel with an average bifurcation ratio of 3.32. As suggested by Horton (Horton, 1945) a bifurcation ratio of 3 or 4 is recommended '*for mountainous or highly dissected drainage basins.*' (Horton, 1945). In such terms, the mean bifurcation ratio of the Paro basin follows the trend mentioned by Horton. The average length ratio of the Paro basin is 2.87. In terms of laws, this ratio and the bifurcation ratio are supposed to approximate a geometric series, inverse for stream numbers and direct for stream lengths (Fig. 4).

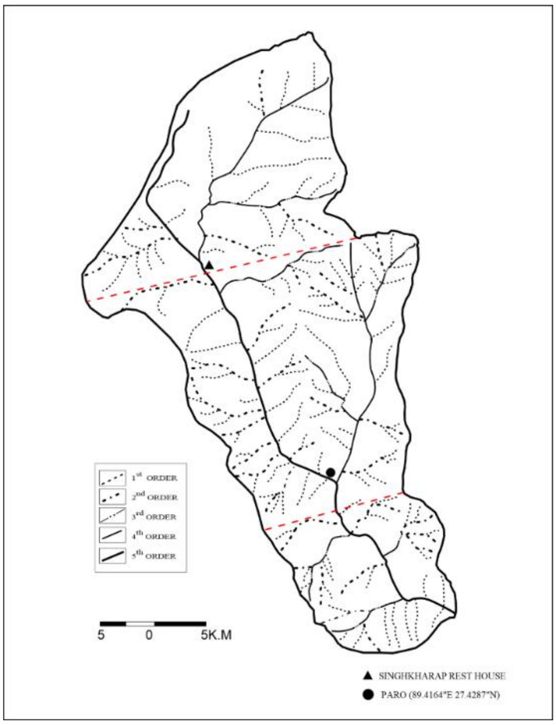


Figure 3: Stream Network & Ordering

Table 2: Observed Linear and Areal morphometric properties of Paro basin

1231.4	456.66	2.7	1	104		3.32	121.66	1.17		2.85	60.83	0.568	0.651
			2	31	3.35		157.75	5.08	4.34				
			3	7	4.43		65.0	9.29	1.83				
			4	2	3.5		49.17	24.59	2.65				
			5	1	2		63.33	63.33	2.58				

Abbreviation used in morphometric Table no. 2

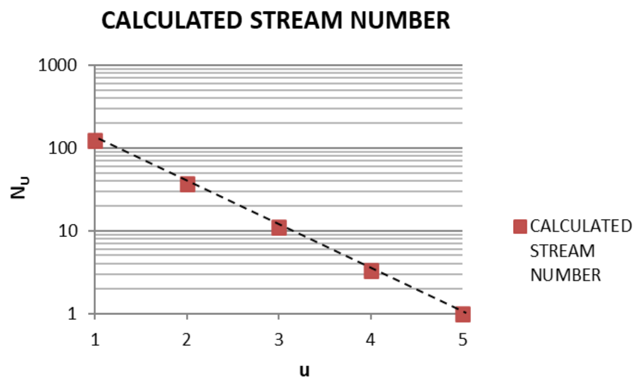
A= Area of basin in km^2
L_s = Length of stream in km
D_d = Drainage density in km/km^2
u = Stream order
N_u = Order-wise number of streams
R_b = Bifurcation ratio
L_u = Order-wise length of streams in km
R_L = Length ratio
L = Length of basin in km
R_c = Circularity ratio
R_e = Elongation ratio

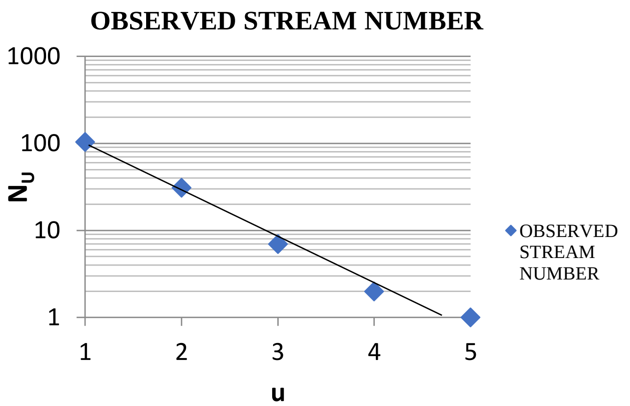
Table 3: Calculated values of N_u and L_u following Horton's Laws

Order of Streams (u)	Number of Streams	Average R_b	Calculated Number of Streams	Mean Length (L_u)	Average Length ratio	Calculated Length of Streams
1	104	3.32	121.49	1.17	2.85	1.17
2	31		36.59	5.08		3.33
3	7		11.02	9.29		9.50
4	2		3.32	24.59		27.08
5	1		1.0	63.33		77.19

Table 4: Deviation of the observed values from calculated values

Stream Order	No. of Streams		Deviation	Mean Stream Length		Deviation
	Observed	Calculated		Observed	Calculated	
1	104	121.49	-17.49	1.17	1.17	0
2	31	36.59	-5.59	5.08	3.33	1.75
3	7	11.02	-4.02	9.29	9.50	-0.21
4	2	3.32	-1.32	24.59	27.08	-2.49
5	1	1.00	0	63.33	77.19	-13.86





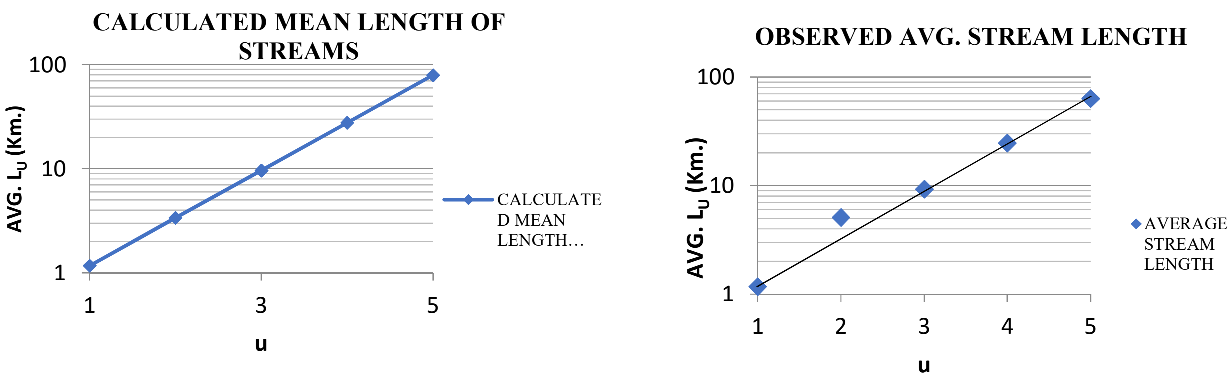


Figure 4: Relation of stream order with stream number and mean stream length

7. Analysis

a) Basin asymmetry

The asymmetry in stream network propagation is observed in the areal expanse of the left and right bank tributary drainage basins (Fig.3). The asymmetry factor determined gives a value of 39, which indicates that the Paro drainage basin is tilted towards the right bank (Fig. 5). This has reduced the scope of stream network elaboration in the right bank, and the areal expanse of the tributary basins has been restricted. The TTSF value obtained is 0.35 or 35. This value is less than 50, indicating that the Paro drainage basin is tilted towards the right bank (Fig. 5).

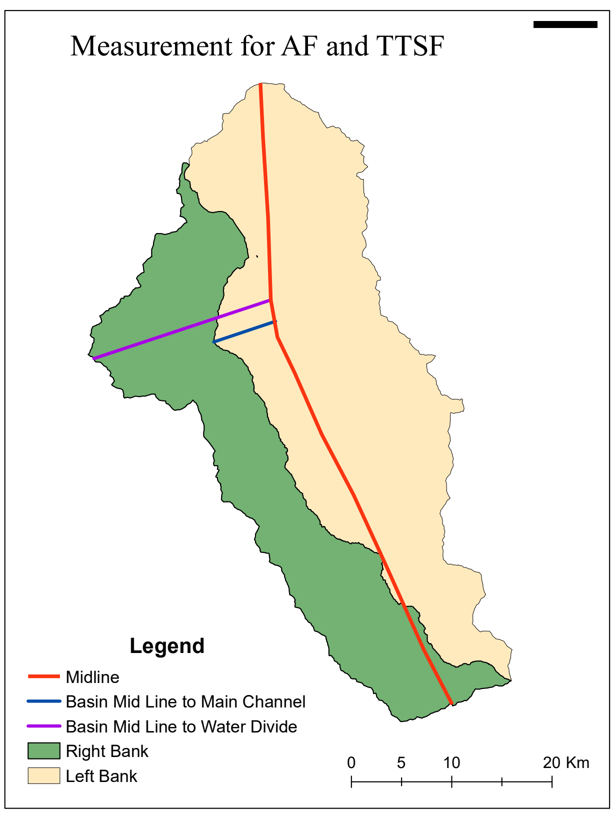


Figure 5: Measurement for AF and TTSF

b) Changing Valley-form

The Paro River is not a long channel (63.33 km.), but the valley-form, as well as bed forms, have an appreciable uniqueness in their characteristics. Such characteristics owe their origin to the
tectonic as well as erosion activities which are well marked in the longitudinal as well as transverse valley-forms of the Paro Basin.

A longitudinal profile constructed (Fig. 6) shows that there is a sharp break at about 3048 m. approx. (10,000 feet), where the channel leaves its canyon section and enters into a narrow valley with a gorge section. This gorge segment has been designated as the upper gorge section in the profile.

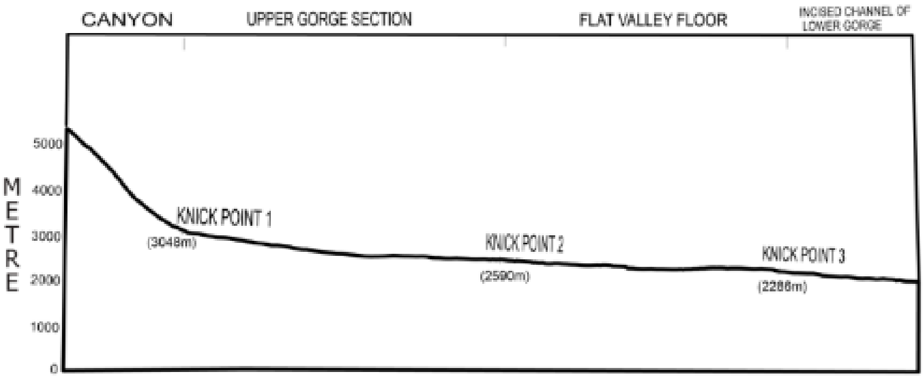


Figure 6: Longitudinal Profile of Paro Chu

This segment continues up to 2590.8 m approx. (8500 ft.) where a nearly flat valley floor is noted. This flat valley, more or less, ends at about 2286 m approx. (7500 ft.) where the valley cross profile again steepens up to its confluence at Chhuzom, which is marked here as the lower gorge section. The incised course with river terraces and gradually rising valley walls runs for about 11.0 km from 27° 21´ 02.27″/89° 27´ 53.77″ near Shaba School to the confluence at Chhuzom.

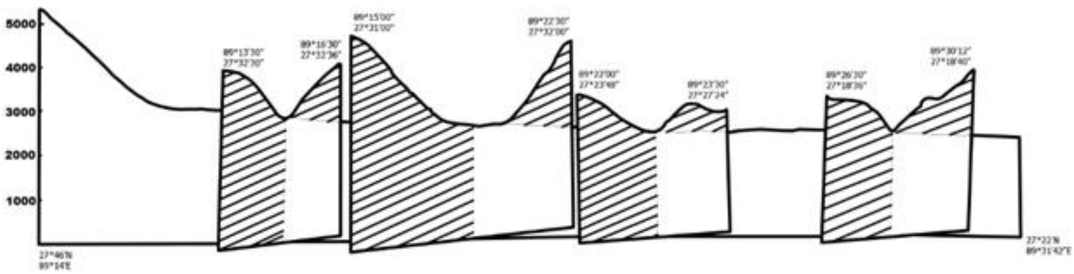


Figure 7: Superimposed transverse valley profiles

Four transverse valley profiles (Fig. 7) have been superimposed on the longitudinal profile. These profiles have been selected from the upper gorge segment as well as in the other downstream segments. In the first profile of the upper gorge segment, it is truly a ‘V’ form of the valley. Then, in the flat valley floor segment, the ‘V’ widens, and the flat floor of the valley is well-marked with the centrally located stream.In the successive lower one, the transverse profile again narrows down, although the flat floor of the valley still continues for a narrower width. In the fourth transverse profile of the valley, the narrow ‘V’ with steep valley walls again appears (Plate 3). The channel at the bottom without any flat valley floor is notable here. This fourth profile has a very steep cliff-like valley-wall (Fig. 7, Plate 4) alike the upper gorge segment.

c) Channel Gradient

The channel gradient of all these four sections of the longitudinal profile varies considerably as noted in the following table (Table 5).

Table 5: Variable gradient of Paro Chu

Channel Segment	Gradient
Canyon	207 in 1000
Upper Gorge	27 in 1000
Flat Valley	12 in 1000
Lower Gorge	39 in 1000

Plate 3: Gorge section in lower course

Plate 4: Cliff on right gorge wall in lower course

Observations made along the course of the channel reveal that in the flat segment of the Paro Valley i.e. in Paro town and some other localities, the channel bed is almost near the valley floor, the bank height is very low, and the channel passes through recent sediments, strewn with boulders (Plate 5 & 6). In this part, the channel frequently changes its flow line between the channel bars, and in some parts, even a braided form is noted. It may be mentioned further that in the immediate lower reach of the breakpoints along the longitudinal profile, two braided parts are well marked. Such a braided section is notable in Plate 7. Here, the river bed is much wider in comparison with the upstream part, and the flow line is divided among multiple number of channel bars.

Plate 5: Shallow meandering course

Plate 6: Shallow channel strewn with in flat valley section boulders in the middle course

Plate 7: Braided Part of Paro Chu

Plate 8: End of braided part, Paro Chu

The braiding index (Brice, 1964) being 4.43 indicates that intensive braiding has taken place. It is obvious that at such physiographic transitions, due to tectonic influence, the rocks are sheared and offer higher erosivity. Beyond this braided part, the channel again narrows and returns to its previous form (Plate 8).
Gradually south-eastward, in the downstream direction beyond Paro bridge, the flow line incises slowly into the bedrock. Thereafter, it incises its course further and deeply cuts through the bedrock. The previous valley floor is left as river terraces composed of the Quaternary sediments of fluvial origin. Tobgay & Hurtado, (2004) observed that the longitudinal profile of the Paro incises into the bedrock, and they also mark "*discrete zones of steep channels adjacent to physiographic transitions*."
However, the breaks of the longitudinal profile are not merely due to differential erosion at lithological contacts. Rather, they indicate changing gradients due to tectonic uplift as well as the dynamic intensity of erosion activated under tectonic influences (Tobgay & Hurtado, 2004). The physiographic transitions give rise to a stepped profile (Norbu et al, 2003). They have noted that
the central as well as the western part of Bhutan the river valleys have shown relatively flatter and wide surfaces having gentle valley-side slopes mostly occurring between the elevation of 1100 m and 2600 m. Thus, with all such evidences, it may be noted that the Paro Chu has been passing through a state of rejuvenation under the impact of neo-tectonic activities. However, rejuvenation produces more sediment. At the confluence of the Paro Chu, this load of sediments cannot be flushed out by the Paro, as it is confronted with a stronger flow of the Wong Chu. As a result, the load of sediments forms a large point

bar on the right bank of the Paro (Plate 1) and the concentration of the flow occurs along the left bank only.

d) River terraces of Paro Valley

A few river terraces are formed at the face of uplift during the course of the incision of the channel, especially in the incised part of the channel. Such river terraces occur as unpaired terraces at the point bars where the channel forms a bend. The entrenchment being slow, it becomes an ingrown meander and gives rise to such unpaired river terraces.

e) Slope

The map showing distribution of the amount of slope (Fig. 8) reveals that in the lower most reach of the valley, the valley-walls are much steeper (45.89° to 54.43°) than that of the middle part where the valley floor is wider and gentle (<10°). This feature indicates an incision and a change of valley-wall slope characteristics.

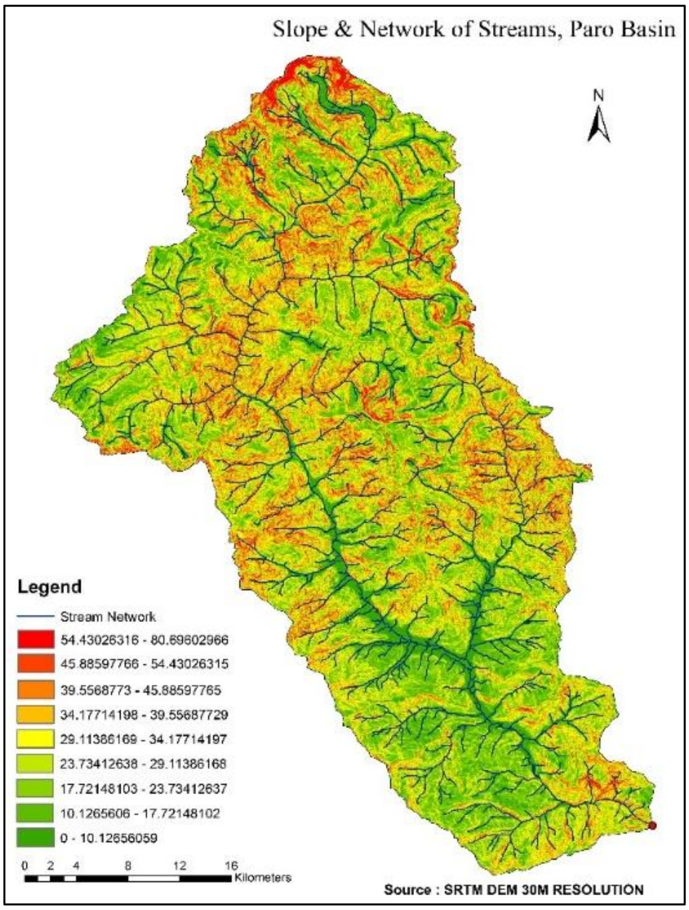


Figure 8: Slope & stream network

8. Discussion

The negative deviation of most stream orders in terms of the number of streams and mean stream length (Table 4) indicates that the lithological character does not allow a uniform scope of erosion and stream initiation. In the case of stream numbers, resistant rocks of the basin have restricted the greater scope of network elaboration. In the case of stream lengths also, only the 2nd-order streams have given a positive deviation; otherwise, in almost all the cases, it is negative. A look into the network of the basin reveals a much greater number of 2nd-order streams than the 3rd-order ones, and the bifurcation ratio between them is 4.43, which is higher than the recommended value suggested by Horton. Hence, 2nd order streams dominate the network.

If the 1st order streams were very high in number in comparison with the 2nd orders, a weak lithologic resistance in the source region could be suggested. But, the bifurcation ratio between the 1st and 2nd orders is at par with the recommended value. On the other hand, a bifurcation ratio of 2 is obtained between 4th and 5th order streams and 3.5 between 3rd and 4th order ones. This again suggests that not much integration and abstraction have taken place in the network.

It appears from the matching of lithological units of the generalized geological map of Western Bhutan (Long et al., 2011), the upper part of the basin upstream of Singkarap Rest House (Fig. 3), there are exposures of the Chekha Formation and Lingshi syncline, and from the immediate north of Paro Dzong, there is Paro window towards the downstream up to the confluence at Chhuzom. Between them, there lie the meta-sedimentary rocks of lower structural level and less intense metamorphism. The Chekha Formation consists of quartzite inter-bedded with biotite-muscovite-garnet-schist (Gansser, 1983) (Long et al., 2011). The Lingshi syncline covering the immediate next part belongs to the old metamorphic rocks of the Paleozoic and the Mesozoic. Then, the basin is again traversed by the Chekha Formation; after that, beyond Singkarap rest house or so, the meta-sedimentary group starts. This unit continues, more or less, up to the immediate north of Paro Dzong, where the Paro window starts. It is in this middle part where the network of the basin is more elaborate, and second-order streams dominate the scenario. When the bifurcation ratio between 1st and 2nd order is checked in the upper segment of the basin beyond Singkarap, it is 4.8; in the middle part, it is 3.29, and in the lower part, it is 2.67. Hence, none of them is beyond 5.0, but in the middle part, when it is checked between the 3rd and 2nd order streams, the bifurcation ratio is 5.67. It indicates a high bifurcation ratio >5 between the 2nd and 3rd order streams, where the basin is much wider than the upper and lower counterparts.

Hence, uniform lithologic resistance cannot be suggested for the entire basin. As far as the resistance to stream erosion is concerned, the meta-sedimentary group of rocks happens to be less resistant than the Chekha-Lingshi-Paro Formations. The Paro Formation is a window; the level of metamorphism is similar to that of the typical Greater Himalayan rocks. Long et al. (2011) consider that the combined data of provenance and metamorphism of the Paro formation may indicate that the rocks are subject to pressure and temperature similar to that of the Greater Himalayan ones. Thus, the network has been less elaborated in the Chekha-Lingshi and Paro formations, whereas it is more elaborate on the meta-sedimentary rocks.

A higher bifurcation ratio between 2nd and 3rd-order streams in the middle part of the basin marks the differential nature of rock resistances in terms of grades of metamorphism. On the other hand, the negative and positive deviation of stream numbers and mean stream length from that of calculated values deducted by Horton's laws further indicate the difference in litho-characteristics.

The maximum deviation of the observed values from calculated values of Laws in stream numbers is noted in first-order tributaries, which specifies the role of tectonic uplifts. In the application of the Law of stream length, maximum deviation is marked in the 5th order, which indicates the further elongation of the main channel at the face of the uplift of the terrain.

The lack of randomness in stream initiation indicates the network to be topologically distinctive. The change in valley-form, as indicated by the transverse valley profiles, reveals that the downstream course of the stream has incised into its past valley floor, resulting in steeper valley-side slopes and higher stream-gradient with the formation of river terraces.

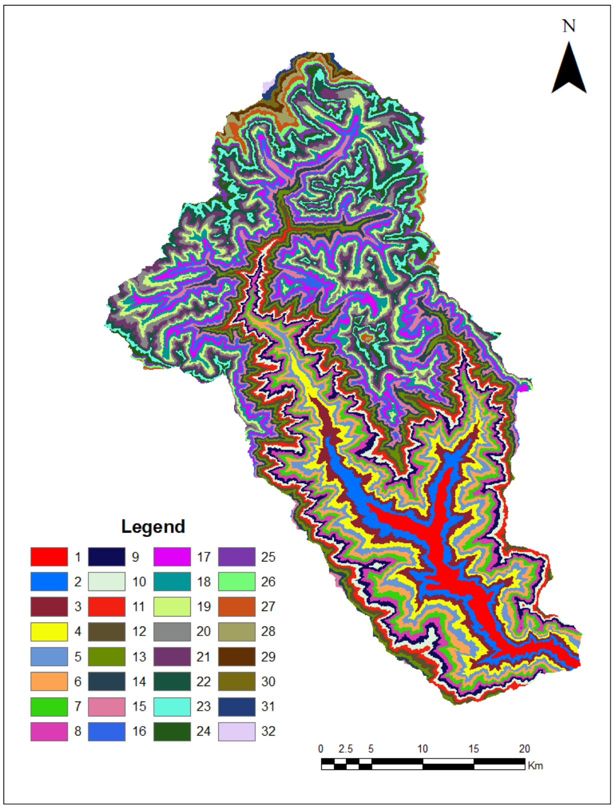


Figure 8: Elevation Zones of Paro Basin

A 30 m resolution DEM is used to construct the hypsometric curve. The hypsometric curve prepared shows variable hypsometric integrals in 32 zones at a regular interval of 100 m (Fig. 8). Out of these 32 integral values, from zone 2 to zone 31 the range of integral values varies between a minimum of 0.427417 and a maximum of 0.515545. All such integral values indicate the stage maturity of the

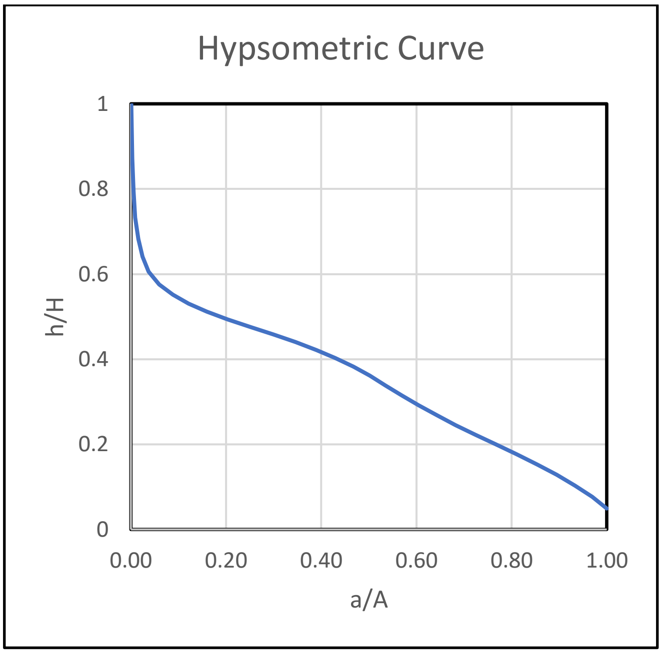


Figure 10: Hypsometric Curve of Paro Basin

landscape of the Paro basin, though the stage of maturity varies in attainment, as the curve is not smooth (Fig.10). This must be related to the variable resistance of lithology of the basin. It has revealed further that that integral values are higher towards lower elevations and lower towards higher elevations. The zones with higher hypsometric integrals indicate their greater proneness to erosion (Singh et. al 2008). The highest elevation zone, i.e. zone 32 gives a hypsometric integral of 0.318149, which indicates an old stage. On the other hand, zone 1 being the lowermost elevation zone having an integral value of 0.714533 attains the stage of youth. Thus, the lowest elevation zone is the most active part of the basin.

9. Conclusion

Thus, it can be concluded that the Paro basin is affected by tectonic movements and the impact of such movements has been catered in different signatures of process and landform, as observed in other Himalayan River Basins too (Goutam & Singh, 2023). The morphometric disparity, the disequilibrium of relief and altitude, the presence of gentler slope in the middle part and steeper slope in the lower part of the valley indicate distinct impact of tectonics on the network of streams. The geological structure and litho-characteristics play important roles in the growth and evolution of the stream network. The lack of topological randomness in the network and deviation from Horton's laws are also related to the same structural influences. The braided reaches also reveal the consequences of neo-tectonic activities on the morphology of the channel.

This research has put forward a methodology for understanding the discrepancies of the Himalayan River basins which are affected by the continuous tectonic movements. This small basin of the Paro Chu has sufficient lithological variation for further microlevel studies of landforms which are the bases of land-based economic development in this crowded stream valley of western Bhutan.

Statements and Declarations

Data Availability: The author declares that the data supporting the findings of this study are available in the paper.

Competing Interest: The author declares that he has no financial or non-financial competing interests.

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