Other Attributes

The area comes out to be 7401.09 sq km. the pattern of the drainage is dendritic and hence the impact of lithology and slope is clearly visible on drainage. Hence, the rocks are of a more homogeneous nature and the geologic structure does not have much control over this (**Figure 2**) [12].

Average Slope of the Watershed

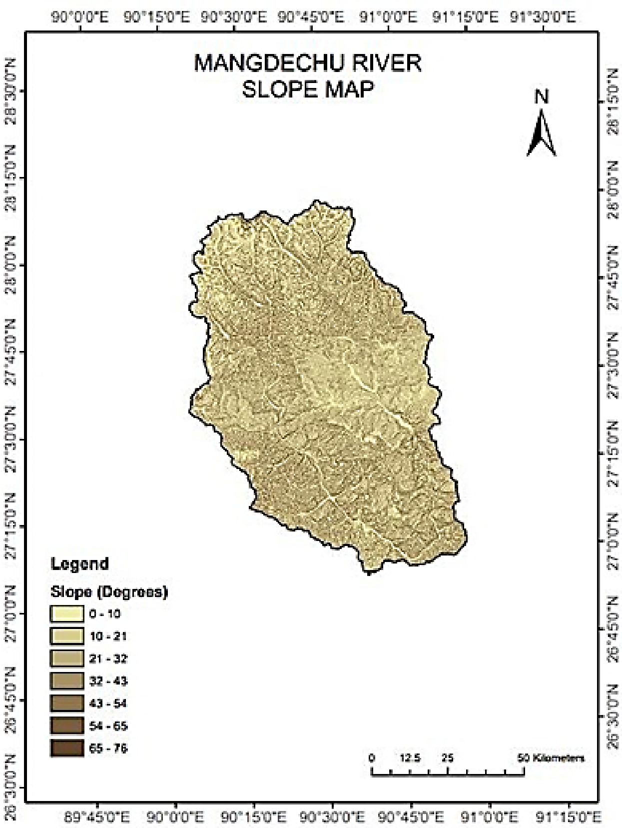
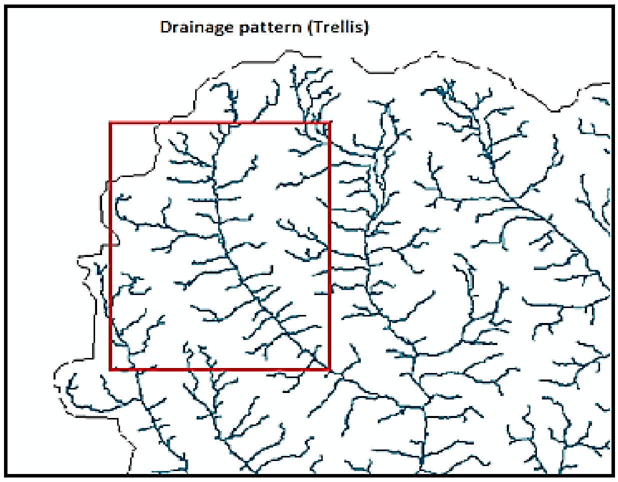


Figure 2: Slope of Mangdechu river basin.

The information about the prediction of edibility can be received by the average slope. In short, when the slope is high, there are higher chances of erosion in the watershed. The slope map shows that the maximum slope in the region is about 76 degrees while starting from 0 degrees. The river valley lies in the high slope region where the slope is almost above 50 degrees but the majority of the area is under the gentle slope. Hence, the region is prone to erosion due to the high slope in the river valley areas. The average slope is 23.96.

Drainage pattern

The region shows a trellised pattern in the upper riparian area and a dendritic pattern in the lower riparian *i.e.* the higher elevation region has the visible impact of structural control (folds and faults) while in the lower region, the rocks are comparatively softer (**Figures 3 and 4**).



Figures 3: Drainage pattern (dendritic) in lower riparian of Mangdechu basin.

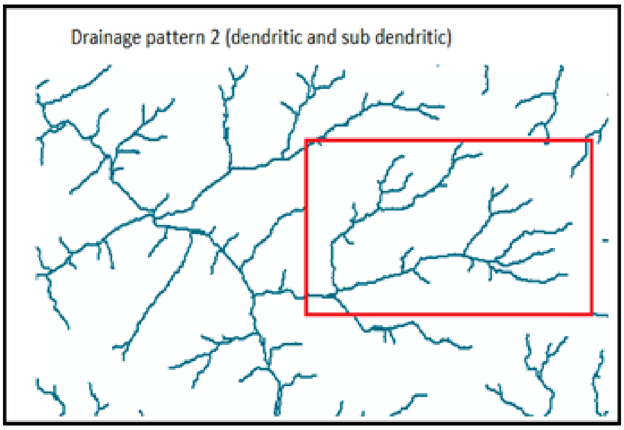


Figure 4: Drainage pattern in the upper riparian region showing structural control.

Linear Aspects

Stream Order (Su): Stream order is the most fundamental unit of morphometric analysis. We have used the Strahler method here for calculating the stream order. Stream order is directly proportional to watershed area. The total number of stream orders here is 7 *i.e.* 1^{st} order, 2^{nd} order, 3^{rd} order, 4^{th} order, 5^{th} order, 6^{th} order, and 7^{th} order. Hence, this is a 7^{th} order watershed. Stream order simply measures the position of a stream in the hierarchy of tributaries. The data proves (through the scattered diagram) that there is an inverse relationship between a stream number and stream order (**Figure 5**).

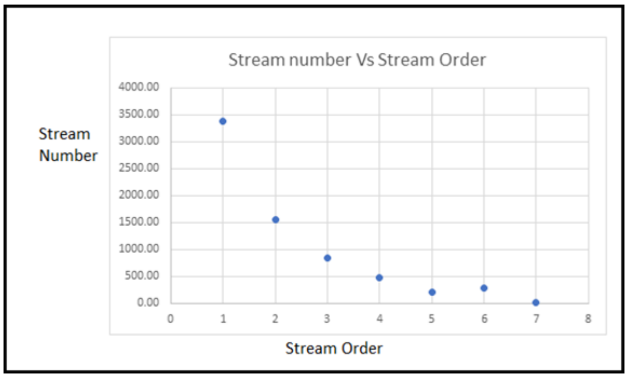


Figure 5: Inverse relationship between stream order and stream number.

Stream Number (Nu): Stream number is the total number of the stream segments of that stream order. There is an inverse relationship between the stream order and stream number *i.e.* higher the stream order, the lesser will be the number of streams of that order. In the Mangdechu watershed region, 3392 streams are first order, 1549 streams are second order, and 844 streams are 3rd order, 473 streams are 4th order, 202 streams are 5th order, 290 streams are 6th order and 3 streams are 7th order (and the total number of the streams is 6753). We saw some discrepancy here since the number of 6th order streams is more than that of the 5th order which is due to a change in topography in the lower riparian. It also reveals that the chances of flooding in the lower riparian area are more since the GIS technique (using the Strahler method) adds up the stream number from node points. The figure shows that there are more streams falling in the 6th order stream and hence input in the 6th stream river is more due to which, it is carrying more water as compared to the other river orders. Here, a large number of 1st and 2nd order streams show heavy runoff load and hence, high chances of flooding in the lower riparian region. High number of lesser order streams means less probability of lower riparian streams having control over flooding (Figure 6).

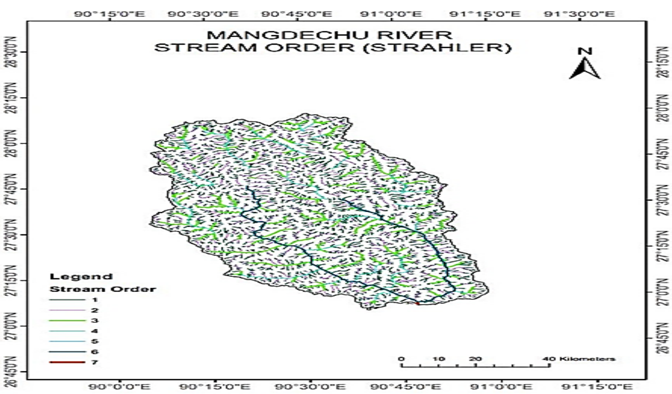


Figure 6: Stream order (Mangdechu river) following strahler method.

Stream Length (Lu)

With the help of GIS techniques, the total stream length of the region is calculated. The total length of the stream is 6310.84 km. A lesser stream length means a steep slope while a larger stream length means a gentle slope. In the Mangdechu watershed, the stream length is more because we have taken a flow accumulation of 1000 which means more streams are shown. If we take flow accumulation into consideration, the length of the streams is not very high which means that the slopes through which the river is flowing are steep. Total stream length is maximum in the first order and it keeps on decreasing further.

Mean Stream Length (Lum)

The formula to calculate Lum is the total stream length of a particular river order divided by the total stream number of that order. The Mean stream length of 1st order streams is 97 km which means that these rivers are short in length and flowing in a steep slope region. 2nd order Lum is 1.03 km, 3rd order Lum is 87 km, 4th order Lum is 77 km, 5th order is 0.66 km, 6th order is 69 km and 7th order is 46 km. The total means stream length is 934 km (934 m). We can conclude that the mean stream length is less which means that the rivers are lesser in length but more in number and the region has comparatively high drainage density and flooding chances. The mean stream length depends on the size and topography of the watershed. The anomaly here in the 5th and 6th order stream is due to stream flow, types of rocks, slope, and topography. Hence, there is a high chance that the region has a sudden change in the rock types and slope causing flood like conditions in the lower riparian area.

Stream Length Ratio (LURM)

It is simply the ratio of the average length segment of any order to the average length segment of the next lower order. The average stream length ratio is 0.89 km. Its value remains almost constant in the watershed. In the Mangdechu river watershed, its value varies between 0.66 km and 1.06 km. This value shows that the rivers are dependent on the slope and topography of the region. Since the stream length ratio is not constant, it shows the late youth stage of the geomorphic development in the region (Figure 7).

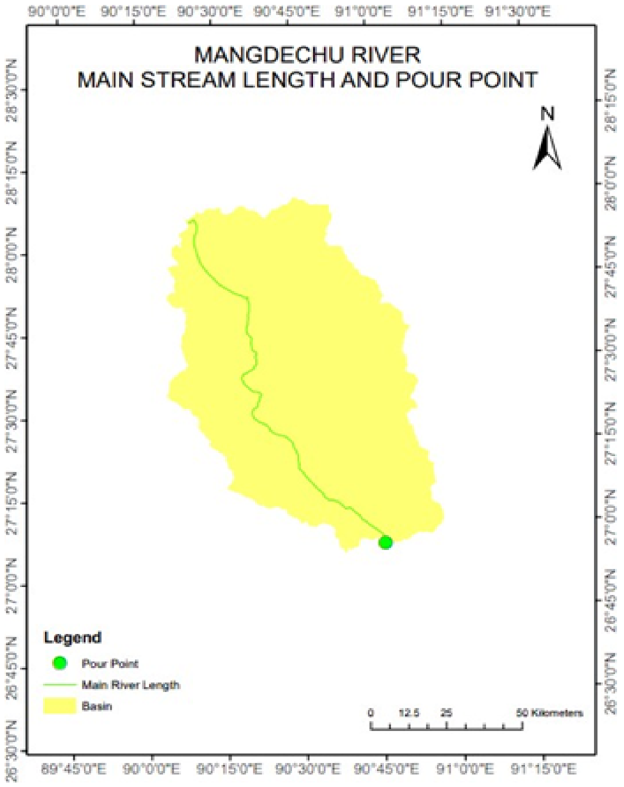


Figure 7: Length of the main stream (155.80).

Bifurcation Ratio (Rb)

This is defined as the number of streams of a given order divided by the number of streams in the higher order. The value of the bifurcation ratio here is between 0.70 and 96.67. The bifurcation ratio reveals the chances of flooding and hence higher the bifurcation ratio; the more will be the chances of flooding. Thus, we can conclude that the high bifurcation ratio of the higher order streams in the region means high chances of flooding in the lower riparian region. Manas national park is located in the lower riparian region and as a result of this there will be more chances of flooding in the region. A general Rb between 3 to 5 means that the rocks are homogeneous while a value of more than 10 means rock structure has a huge control on the elongated basin. Also, high Rb means a low infiltration rate and more surface runoff (Table 1).

Table 1: Morphometric analysis of Mangdechu River and threat to Manas.

Stream order	Stream number	Stream length (km)	Bifurcation ratio	Mean stream length
1	3392	3282.93	2.19	0.97
2	1549	1591.29	1.84	1.03
3	844	733.91	1.78	0.87
4	473	366.22	2.34	0.77
5	202	134.03	0.7	0.66
6	290	201.08	96.67	0.69
7	3	1.38		0.46

Weighted Mean Bifurcation Ratio (RBWM)

Strahler found a method to find out RBWM by multiplying the Rb of an ordered stream by a total number of streams involved in the ratio.

Length of the Main Channel

The main channel length is 155.80 km which means that the main channel is quite long and many other streams are falling into it covering a larger drainage basin area and hence high chances of flooding.

Basin Length

The basin length is 128.80 km which means that the river basin is more elongated and hence, there is a high chance that it is coming from steep slopes thus, in the lower riparian area, there must be more rivers falling into the main channel arising flood like conditions.

Rho Coefficient (runoff coefficient)

The coefficient relates drainage density to the physiographic development of a watershed. It also finds out the storage capacity of the network. It depends on various factors further like climate, geology, land use, and anthropogenic factors. It is simply defined as the ratio between stream length and bifurcation ratio. For Mangdechu river, the rho coefficient values are written in the table. A high value means high hydrologic storage during floods while a low value will low storage during floods. The table represents that lower order streams have the ratio less than. 50 *i.e.* low hydrologic storage. 5th order stream has comparatively high hydrologic storage. While the value for the higher order stream is extremely low *i.e.* most of the water goes as runoff and hydrologic storage capacity is very low. The average value if also very low. Hence, we can conclude that the river basin has less infiltration capacity during floods (Table 2).

Table 2: Rho coefficient.

Stream length ratio	Bifurcation ratio	Rho coefficient
1.06	2.19	0.48
0.85	1.84	0.46
0.89	1.78	0.5
0.86	2.34	0.37
1.05	0.7	1.5
0.66	96.67	0.01
5.36		
	Average Value	0.059

Areal Aspects

Area: The area of the Mangdechu basin is 7401.09 sq km covering a large chunk of land.

Drainage Density

It is defined as the ratio of total stream length of all the orders per unit basin area. It tells about a basin's runoff potential. The higher the drainage density, the more will be the runoff. It also depends on climate and vegetation, properties of the landscape, and relief. The drainage density of the AOI is 853 km/sq km. the drainage density is low due to the large area of the basin and hence there is a coarse drainage texture. Most of the dams are built in the region of high drainage density (due to high runoff and for flood control). Tongsa dam is also located in a comparatively high density drainage region. But, its large capacity can have direct control on the flow of the Tongsa/Mangdechu River since the release or store of water in the dam will regulate the supply of water to the Manas national park making it necessary to have a say between the countries to regulate its water (Figure 8).

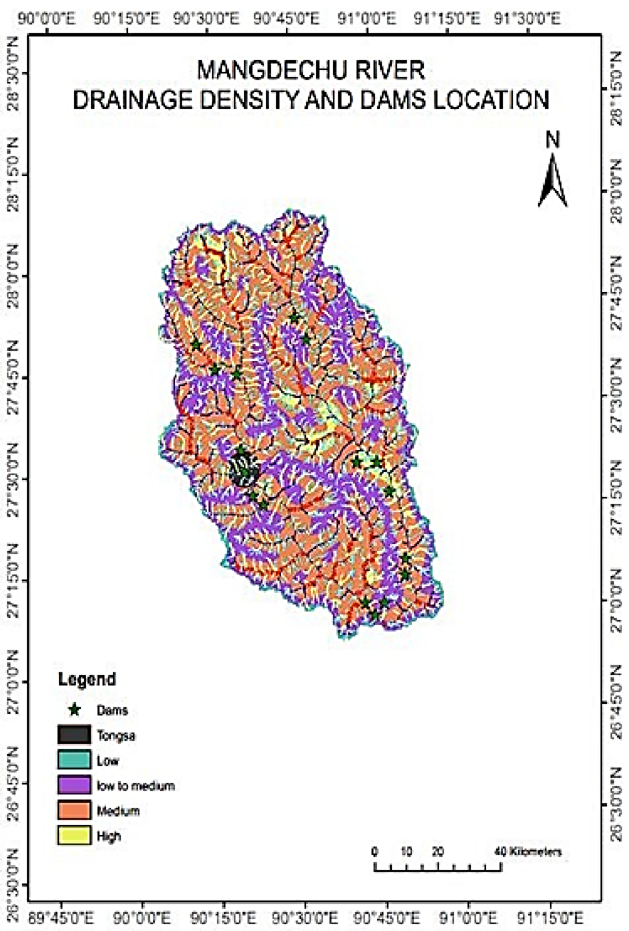


Figure 8: Drainage density and location of dams.

Stream Frequency

It is defined as the ratio between the total number of streams and the total area of the region. When the value of stream frequency is high, it means the surface runoff is high. The value is 0.91 per sq km for Mangdechu river. Again, the value is low due to the high drainage area. It means that the frequency of the rivers is not extremely high but the amount of water, the rivers are carrying is quite high due to the high slope. Low stream frequency also reveals that the region has hard and resistant rocks.

Drainage Texture

It gives information about channel spacing. It is also influenced by vegetation cover, and drainage density. If the rocks are massive and resistant, the drainage texture will be coarse. The drainage texture in the area of interest is coarse.

Length of Overland Flow

A simple formula to calculate the value is the reciprocal of drainage density divided by two. Hence, it shows the spread of water over the ground before it gets settled down in the mainstream. The value is 0.58 for Mangdechu river which means there is a high impact of structural disturbance in the region and permeability is low and surface runoff is high. Hence, the river has the potential to create more flood like conditions.

Constant of Channel Maintenance (Cc)

It is the inverse of drainage density. The value is 1.173 for the Mangdechu river which means there is a high infiltration rate and permeability and the surface runoff is comparatively low. In short, the structure does not have a very wide impact on the watershed.

Basin Configuration

It gives information about the shape of the basin. Scum said that the round basin has a high probability of facing floods due to high chances of erosion. Also, region of high relief has high transport capacity leading to induced flood like conditions.

Form Factor

It is defined as the ratio between the drainage area and the square of maximum basin length. The value for Mangdechu is 45. It gives information about flood formation, erosion potential, and the capacity of the stream to transport sediments. Its value ranges from 0 to 1 where 1 means perfect circular while 0 means perfect elongated. The value here shows that the basin is nearly a mix of both circular and elongated which means there are medium chances of erosion, it has the medium capacity to carry sediment load and as a result of this, we can expect flood conditions to arise in the lower riparian.

Circulatory Ratio

It is defined as the ratio of basin area and circle area that we can make with the same perimeter as the basin. The value is 40 for the basin which means it is nearly elongated and the rocks are permeable. It further shows the influence of land use, slope, relief, and the structure of geology in that region.

Elongation Ratio

It is defined as the ratio between the diameter of a circle that has the same area as the basin has and the maximum basin length. The value is 75 for Mangdechu basin which means that the basin is almost oval shaped. Hence, relief is medium and the slopes are gentle to steep.

Shape Index

This value is reciprocal to the form factor. For the Mangdechu river, the value is 2.22 which means that the basin is oval shaped and the flood discharge period is weak to moderate (Figure 9).

Relief Aspects

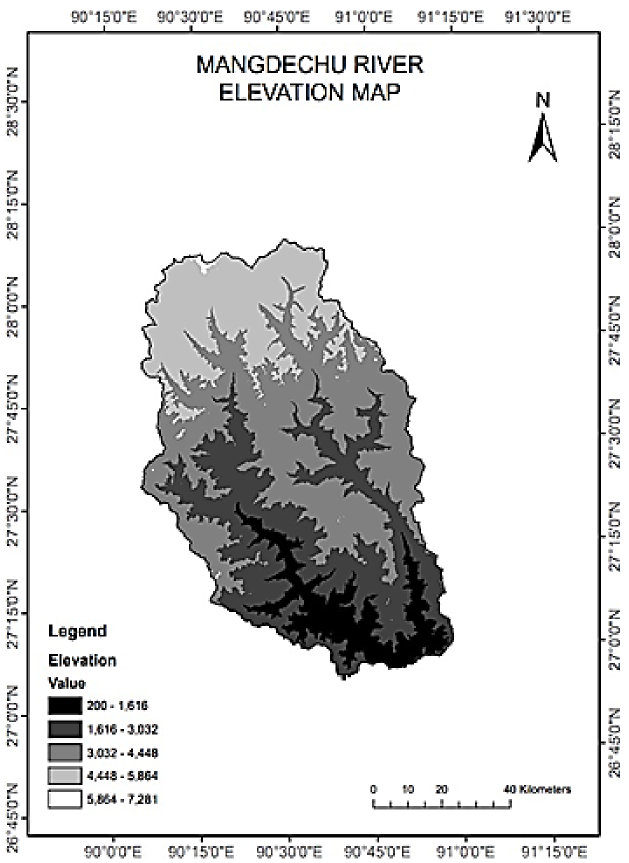


Figure 9: Basin relief map of Mangdechu river.

Basin Relief

This is defined as the value we get by subtracting the lowest point from the highest point of a region. This is an important factor for getting information about the gradient of the river and the sediment volume it can carry. It gives information about denudation characteristics as well. The value for Mangdechu is 7081 m which is quite high and perhaps one of the most important parameters of the study since it gives clear cut information about the velocity of the streams and their sediment transport capacity.

Relief Ratio (RR)

It is defined as the ratio between the relief of the basin and the length of the basin. It further gives information about the gradient of the region. The value is 0.06 for Mangdechu which is very high, suggesting that the slope is steep in the region and the erosion processes are quite active, especially in the lower riparian where there is a sudden change in the slope and sudden increase in the velocity of the streams.

Ruggedness Number (RN)

It gives a result considering slope steepness and its length. This is calculated as the multiplication of basin relief and density of the drainage. In short, it gives you an idea of how rough the surface is in the basin. The value for Mangdechu is 6.03 which mean that the basin is highly prone to erosion and the slopes are very steep.

Gradient Ratio (RG)

It gives information about the slope of the channel and with the help of this; the volume of the river runoff can be calculated.

Dissection Index

It gives information about the degree of vertical erosion happening in the region and is defined as the ratio between the maximum relative relief and the maximum absolute relief. Its value can be between 0 (means old stage and subdued relief) to 1 (young stage). Absolute relief simply means the maximum height of a region from the mean sea level. While relative relief is the difference between the highest to the lowest point of the region. The dissection index here is 97 which is very high and means that the river is in its young stage and has a high potential for erosion and flooding. The rivers are dissecting their valleys very steeply and have a very high slope.

Melton Ruggedness Number (MRN)

It gives information about the ruggedness of the basin and is calculated as the ratio between basin relief and the square root of the catchment area. The value is 82 for Mangdechu which means a strong relief and steep slope of the ground hence the flow of the river is not normal and the debris flow is quite high.

CONCLUSION

With the help of all the information that we got through linear, areal and relief morphometric analysis, we can conclude that the river flows through a very uneven topography (due to its high ruggedness index, high relief ratio and other areal aspects), has a steep slope (due to its high average and relative relief and high relief ratio) and also very high potential to cause floods in the lower riparian area if its flow is not monitored regularly. Since Manas national park (which is also a UNESCO site) is located very close to the Mangdechu river basin, any step of building a mega dam taken by the Bhutan government should not be overlooked by the countries of low riparian. In the future, it might cause a flood like situation again killing a large chunk of diversity in the UNESCO site and causing a very long lasting devastating effect. The world today belongs to those who have the strength to fight every dynamic situation. Each and every country in the lower riparian should be given data related to any dam built by a country lying in the upper riparian and has real control of a river.

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