Spatio-Temporal Morphological Changes Of The Cagayan River Section In Tuguegarao City, Philippines

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Abstract
Rivers are an essential part of the earth's systems, providing humans with a variety of services. However, natural and anthropogenic factors have resulted in a global degradation of river health despite our reliance on rivers. Such factors have led to fluvial processes such as floods, channel migration, and riverbank erosion, posing a significant threat to humanity. The controlling factors working at various spatial and time scales within the Cagayan River section in Tuguegarao City will be discussed in this study. In addition, spatio-temporal analysis of the river will be conducted using Remote Sensing and Geographical Information System (GIS) technologies to determine river morphological changes and erosion detection on a long timescale (1985-2020).

Index Terms—fluvial processes, channel migration, riverbank erosion, spatio-temporal analysis.

INTRODUCTION

Tropical rivers, like Cagayan River, are typically characterized by pronounced seasonal changes in precipitation, large sediment loads and high rates of lateral channel migration across often very low-gradient and densely populated floodplains (Dingle et al., 2019). Cagayan River and its tributaries are subject to extensive flooding especially during the rainy season. However, natural forces alone do not cause floods. Rather, floods are a by-product of the interaction between natural events and human activities. Nevertheless, many anthropogenic land usage patterns are clustered along the river and near floodplains and submergible areas. Cities with a high population, such as Tuguegarao City, are particularly vulnerable. Significant destruction, and losses of property, life, and money are the results of catastrophic floods. Along with flooding, channel migration and riverbank erosion are dynamic fluvial processes that pose a significant danger to human development along the river and its floodplain. Because of such, the geomorphology of the river system is affected by continuous changes in land use and climate.

Risk analyses, flood mitigation plans, and climate-responsive integrated master plans have been devised for the Cagayan River Basin to resolve the problem. However, humans continue to inhabit floodplains, underestimate the risks of those disaster zones, mismanage flood hazards, overdevelop soil, and deplete natural resources at rates that the natural environment cannot cope with or adapt to (Gacu et al., 2022). Thus, it is important to look at how previous events influenced the geomorphology of the river channel to predict long-term flooding hazards. Looking at trends over time will be a key determinant of vulnerability along the river area. Climate change could also contribute to the changes in river morphology due to significant changes of water flowing in to the channels (Monjardin et al., 2019)

METHODOLOGY

Geomorphic theory and field studies are required to analyze field-collected data during monitoring activities over the eight time periods (1985–2020) of the Cagayan River, which encompasses Tuguegarao City and to evaluate channel conditions and define channel characteristics and types.

A. Gathering of Satellite Images

Landsat images (from 1990 to 2020) obtained from USGS Earth Explorer, its corresponding satellite, collection and level, and the date the image was acquired were all summarized in Table II-1. The Landsat images were projected to WGS 84 UTM Zone 51N. Scanline errors were found in the years 2005, 2010, 2015, and 2020. These errors were fixed in QGIS using the gap mask included in the downloaded file of each corresponding year. There was no readily available Landsat Image for the year 1985 that can be found so a Google Earth image was acquired for that year. Ground Control Points (GCP) were assigned to the image and were georeferenced using ArcMap.

Table 2.1. List of acquired Landsat Images from USGS Earth Explorer

Year	Satellite	Collection and Level	Date Acquired
1990	Landsat 5	C2-L2	July 15
1995	Landsat 5	C2-L2	May 26
2000	Landsat 7	C2-L1	May 31
2005	Landsat 7	C2-L1	May 13
2010	Landsat 7	C2-L1	March 24
2015	Landsat 7	C2-L1	June 16
2010	Landsat 7	C2-L1	June 07

B. Delineation of Channel Centerline

Bank lines of the Cagayan River were manually digitized and extracted to fit along the boundary which encompasses Tuguegarao City. The channel planform maps were processed using ArcMap tools which produced individual channel centerlines for eight time periods.

Once a channel centerline was produced, meander geometric parameters were identified for individual bends of each year (Figure II.1). Such parameters are the: channel length; the straight distance along the river valley, also called the valley length; meander wavelength (λ); sinuosity ratio (P); and the radius of curvature (R_c). The measurements of each meander parameter were identified using the ArcMap measuring tool.

As soon as the meander geometry was measured and identified, a set of points was superimposed on the channel centerline of each year with every distance of 500 m. Following the method described by Lagasse (2004), the points were overlain on the centerline of each year, and a circle was inscribed on each of the meander bends that best fit the set of points assigned and best described the bend. The centroid of the inscribed circle represents the center of the bend, and the radius of the circle signifies the radius of curvature of the meander bend. The half-wavelength (λ) of the meander was delineated from the upstream crossing to the downstream crossing of each bend. The meander amplitude (A) was identified from the midpoint of the wavelength extending to the furthest point of the concave bend.

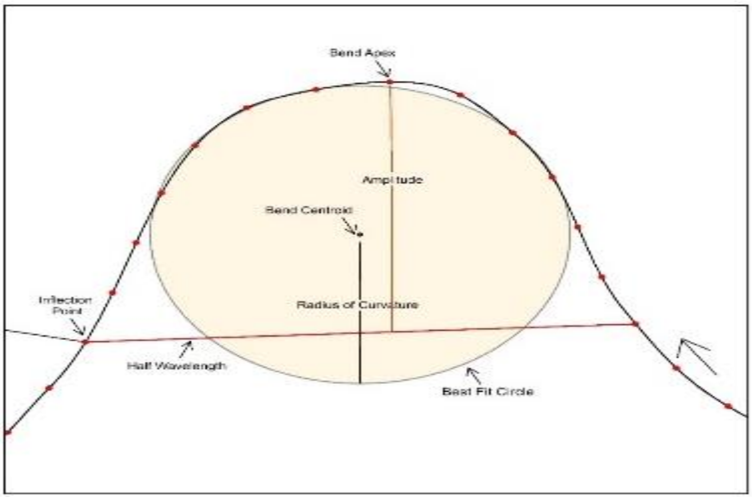


Figure 2.1 Meander bend parameters created using ArcMap.

C. Measuring the Channel Migration

To acquire the amount of change in lateral positions of the Cagayan River section in Tuguegarao, an ArcGIS extension published by the Department of Ecology State of Washington was utilized. The Channel Migration Toolbox aids in automating the measurement of channel migration rates using GIS. The toolbox contains four tools, but only the reach-average channel migration tool was used and desired in this study. The tool measures the channel migration area and the total length of a channel reach given multiple historical time periods. A geodatabase containing the sequential channel centerlines from 1985 to 2020 was created as this was needed as input to make the tool work. A reach boundary perpendicular to the ends of the channel centerlines was also made to define both ends of the channel reaches. The average measurement of the valley length was also required as an input to run the tool and a field name on the attribute table for each year was also made.

After proceeding with the toolbox, the output produced was automatically stored in an output geodatabase created. The outputs were all polygon feature classes representing the channel centerline migration during the seven time periods – 1985 to 1990, 1990 to 1995, 1995 to 2000, 2000 to 2005, 2005 to 2010, 2010 to 2015, and 2015 to 2020. Along with the migration polygons, an attribute table was also generated, which contains the migration summary and has the full report of the migration measurements for each time sequence that was measured, such as the migration area, the beginning and end years of the period analysed, and the averaged total of the migration for the reach length. A "shape length" field wasadded to the attribute table for each of the migration polygons, which contained the perimeter of the whole polygon area.

With the values gathered, the average lateral change of the channel was computed using the method of Micheli and Larsen (2010). The lateral migration rate of each polygon over a time interval was calculated as the migration polygon area divided by one-half of the polygon perimeter (Eq. 1). Afterwards, the annual migration rate was computed by dividing the migration rate by the number of time intervals, which is five years. The data gathered for predicting the channel migration was summarized in Table 4.

$$Migration\ \ Rate = \frac{Migration\ Area}{\frac{1}{2}\ Perimeter\ of\ Migration\ Polygon} \qquad [1]$$

D. Detecting Erosion and Sediment Deposition

Areas of erosion and accretion were determined by using the changes in the locations of both riverbanks during the eight time periods: 1985 to 1990; 1990 to 1995; 1995 to 2000; 2000 to 2005; 2005 to 2010; 2010 to 2015; 2015 to 2010. The extracted river shapes along the Tuguegarao boundary were used and processed by using GIS to create polygons that represented the difference between the two positions of a riverbank area. Through the application of erase and merge tools in ArcMap, the areas of erosion and accretion were determined. The polygon area that has increased and showed movement towards land denotes erosion. On the other hand, accretion is characterized by riverward movement. The areas of erosion and accretion were also calculated separately for each side of the river by using the erase tool on ArcMap. In the study of (Monjardin et al, 2021) sediments accumulate in river bends and mostly in the downstream portion of the river.

E. Land Cover/Land Use Changes

Land Use/ Land Cover analysis has been carried out using ArcMap processing features. Noise reduction and essential radiometric corrections of the Landsat images were made for the years 1985 and 2020. The Landsat images were processed using supervised classification under a maximum likelihood classification algorithm. For the analysis, the images were divided into five (5) classes, all of which are the identified land use/land cover types within the study area – water body, built-up areas, agricultural land, bare soil, and vegetation, respectively. The LULC analysis was made to compare the changes in the land use cover and to identify the relationship and better understanding on the influence of various factors to the changes in the geomorphology of the Cagayan River section in Tuguegarao City. LULC changes also affects the volume of water that might accumulate in natural river channels in the area (Caja et al, 2018).

RESULTS AND DISCUSSIONS

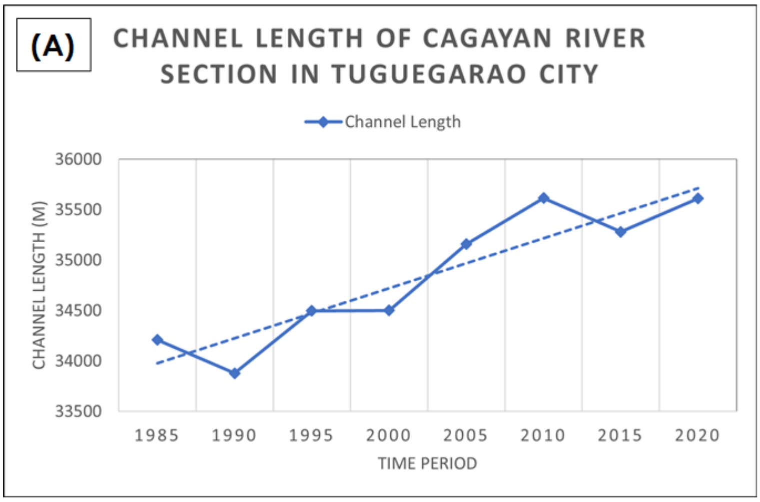
Geometric Parameters of Meander Bends.

Two sets of meander bend were identified, and their geometric parameters were measured with the help of ArcMap tools.

Table 3.1. Sinuosity Ratio and Pattern Classification of Cagayan River Section in Tuguegarao City

Year	Channel Length (m)	Valley Length (m)	Sinuosity	Classification	
				Schumm (1963)	Charlton (2007)
1985	34208.37	19850.17	1.72	Irregular Meander	Meandering Channel
1990	33877.73	19870.91	1.7		
1995	34497.03	19857.26	1.74		
2000	34500.71	19847.3	1.74		
2005	35158.4	19825.48	1.77		
2010	35614.58	19833.35	1.8		
2015	35279.5	19832.01	1.78		
2020	35610.48	19821.63	1.8		
Average	34843.35	19842.26	1.76		

The measurements acquired from the channel and valley length aided in computing the sinuosity ratio (P) of the channel and the obtained values were summarized in Table III-1. Channel lengths acquired during the eight-time period tended to increase relatively over time (Fig.III.A) having an average of 34843.35 meters, contrary to the measurements of the valley length, which gradually decreased (Fig. III.B) with an average of 19842.26 meters. Also, a significant decline was evident in the valley length of the year 2005. The sinuosity ratio of the channel has maintained its range between 1.70 to 1.80 showing a gradual increase throughout the whole study period with an average sinuosity of 1.76 (Fig. 3.2). (Monjardin et al., 2023) showed that sediments accumulates in parts of river with high sinuosity.



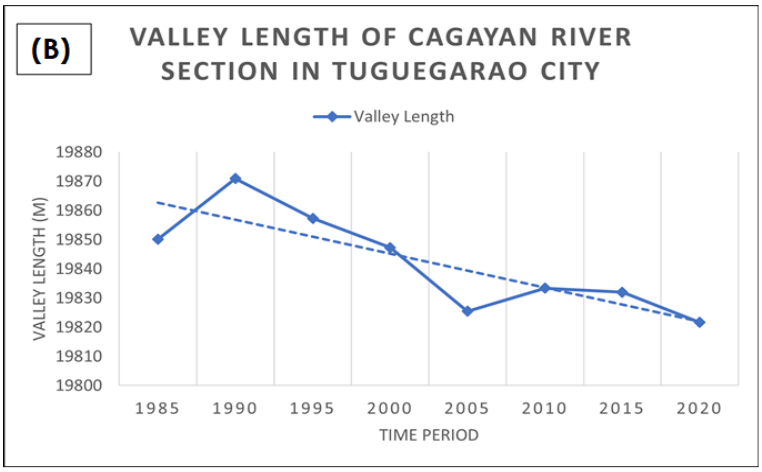


Figure 3.1. Variations in measurements of Cagayan River Section dimensions. (A) Channel Length over the eight time periods; (B) Valley Length over the eight time periods.

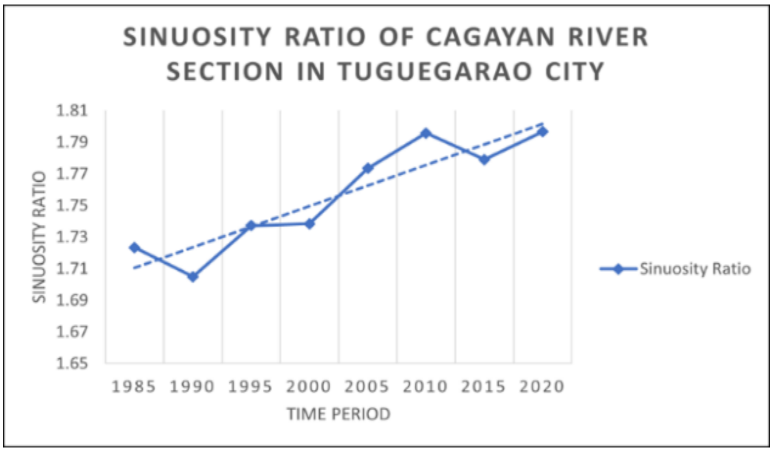


Figure 3.1. Variations in the Sinuosity Ratio of the Cagayan River Section in Tuguegarao from 1985 to 2020.

Best fit circles were overlain on two meander bends identified on the automated channel centerlines for the year 1985 and 2020 (Fig 3.10). The two known meander bends were manually measured for the whole eight time periods and the summary of the measurements is listed in Table III-2. The half-wavelength (λ) measurements obtained from meander bend 1 showed constant values with an average of 2620.45 meters, while the meander bend 2 showed inconsistencies displaying a sudden increase in 1995 and 2000, with the measurements having an average of 3815.72 meters. Meander amplitude (A) measurements for meander bends 1 and 2 gradually increased over time, averaging 1773.88 meters and 2309.65 meters, respectively. The radius of curvature (Rc) acquired from meander bend 1 displayed constant values from 1985 to 2015, with a sudden increase in 2020, while having an average of 1067.88 meters. In contrast, the measurements acquired from meander bend 2 tended to decrease over time and have an average curvature value of 1524.50 meters.

Table 3.1. Measured Geometric Values for Meander Bends 1 and 2 along Cagayan River Section, Tuguegarao City from 1985 to 2020.

Year	Half Wavelength λ (m)		Amplitude (m)		Radius of Curvature (m)	
	Bend 1	Bend 2	Bend 1	Bend 2	Bend 1	Bend 2
1985	2679.3	3804.27	1598.84	1927.83	1080.67	1724.88
1990	2618.54	3798.95	1638.54	2069.51	1086.19	1634.16
1995	2597.92	3927.36	1642.5	2341.42	1081.34	1467.36
2000	2530.86	3961.5	1663.38	2303.61	1007.16	1507.05
2005	2625.26	3756.61	1913.76	2355.24	1062.07	1494.15
2010	2632.63	3835.85	1908.19	2568.41	1035.36	1475.95
2015	2622.49	3694.23	1928.32	2382.43	1013.11	1407.18
2020	2656.59	3746.96	1897.47	2528.75	1177.14	1485.24
Average	2620.45	3815.72	1773.88	2309.65	1067.88	1524.5

Extent and Magnitude of Lateral Migration

With the help of Channel Migration Toolbox, the measurements for the migration area and its perimeter were automatically calculated (Table III-3). A substantial increase in migration area was seen throughout the year 2000 to 2005, taking up 3168138.08 m^2. Also, a distinct increase in migration rate was evident during the same period, having a 90.87 meters rate of migration, while minimal migration occurred during the year 1995 to 2000, having 46.18 meters of migration rate. The migration rate for individual year was measured to be 12.91 meters per year on average (Fig. III.3), while an average of 64.46 meters during the 5-year interval for the eight-time periods. However, as the channel migrates through time, the perimeter of the overall migrated area increases from 68145.01 meters to 70897.35 meters.

Table 3.2. Measured Lateral Migration Values along the Cagayan River Section in Tuguegarao City from 1985 to 2020.

Time Period	Migration Area (m^2)	Perimeter (m)	Migration Rate (m)	Migration Rate per Year
1985-1990	1864771.44	68145.01	54.73	10.95
1990-1995	2078891.25	68391.56	60.79	12.16
1995-2000	1593618.1	69016.95	46.18	9.24
2000-2005	3168138.08	69728.46	90.87	18.17
2005-2010	2424742.2	70803.92	68.49	13.7
2010-2015	2401715.7	70956.84	67.7	13.54
2015-2020	2239558.34	70897.35	63.18	12.64
Average	2253062.16		64.56	12.91

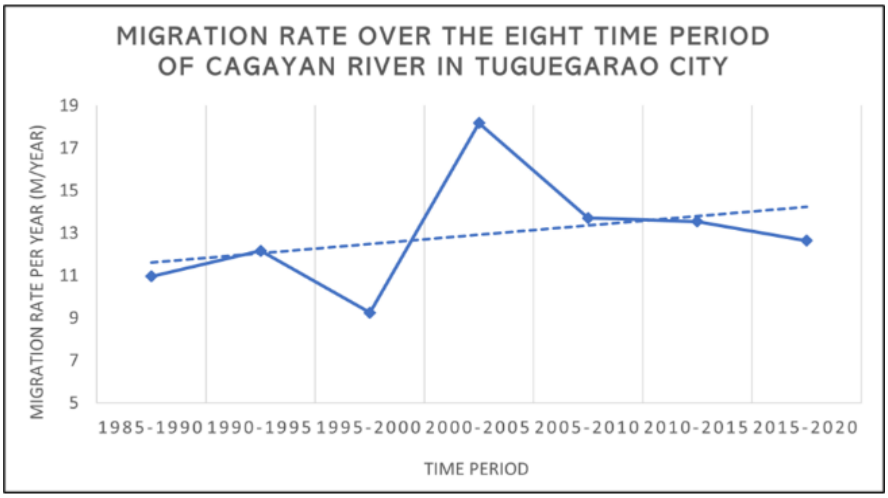


Figure 3.2. Lateral Migration Rate of the Cagayan River Section in Tuguegarao City from 1985 to 2020.

Erosion and Sediment Deposition

The areas and rate of accretion and erosion along the Cagayan River Section in Tuguegarao City are shown in Table III-4 and Table III-5. Throughout the study period, the total area of accretion was 12.75 km^2 while the total area of erosion was 13.49 km^2. Over the seven time periods that were observed, the rate of erosion exceeded the rate of accretion for four time periods: 1985 to 1990; 1995 to 2000; 2005 to 2010; 2010 to 2015. This was reversed for three time periods (1985 to 1990, 1995 to 2000, and 2015 to 2020) with a relatively higher rate of accretion.

Comparison of the areas of accretion and erosion is observed on the left and right banks of the channel. The left bank is observed to have greater areas of accretion compared to the right bank. The total area of accretion was 7.27 km^2 on the left bank and 5.48 km^2 on the right bank. Area of accretion on the left bank exceeded the area of accretion on the right bank for five time periods except 1990 to 1995 and 2010 to 2015. Furthermore, the left bank was also observed to have a greater area of erosion during five time periods except 1985 to 1990 and 2015 to 2020. The total area of erosion was 6.77 km^2 on the left bank and 6.72 km^2 on the right bank.

Table 3.3. Area and Rate of Accretion along Cagayan River Section in Tuguegarao City from 1985 to 2020.

Time Period	Area of Accretion (km^2)			Rate of Accretion
	Left Bank	Right Bank	Total	(km^2/y)
1985-1990	0.67	0.21	0.88	0.18
1990-1995	1.2	1.27	2.47	0.49
1995-2000	0.44	0.16	0.61	0.12
2000-2005	2.28	2.12	4.4	0.88
2005-2010	0.97	0.77	1.74	0.35
2010-2015	0.11	0.21	0.32	0.06
2015-2020	1.6	0.74	2.34	0.47
Total	7.27	5.48	12.75	

Table 3.4. Area and rate of Erosion along Cagayan River Section in Tuguegarao City from 1985 to 2020.

Time Period	Area of Erosion (km^2)			Rate of Erosion
	Left Bank	Right Bank	Total	(km^2/y)
1985-1990	0.95	2.09	3.05	0.61
1990-1995	0.48	0.42	0.9	0.18
1995-2000	1.41	1.32	2.73	0.55
2000-2005	0.29	0.24	0.53	0.11
2005-2010	1.03	1.01	2.04	0.41
2010-2015	2.29	1.24	3.53	0.71
2015-2020	0.32	0.4	0.72	0.14
Total	6.77	6.72	13.49	

The area of left bank erosion exceeded the area of the left bank accretion for four time periods except 1990 to 1995, 2000 to 2005, and 2015 to 2020. However, the total area of the left bank erosion through 1985 to 2020 was 6.77 km^2 which is less than the area of left bank accretion (7.27 km^2). Moreover, the area of right bank erosion also exceeded the area of right bank accretion for four time periods except 1990 to 1995, 2000 to 2005, and 2015 to 2020. Through 1985 to 2020, the total area of right bank erosion (6.72 km^2) was significantly higher as compared to the total area of right bank accretion (5.48 km^2).

Figure 3.4 shows the comparison of the rate of accretion and rate of erosion. For every period, there is a significant difference in the rate of accretion and erosion except during 2005 to 2010. The highest rate of erosion (3.53 km^2 y^{-1}) occurred from 2010 to 2015 while the highest rate of accretion (4.40 km^2 y^{-1}) occurred from 1990 to 1995. On the other hand, the lowest rate of erosion (0.11 km^2 y^{-1}) occurred from 2000 to 2005 while the lowest rate of accretion (0.06 km^2 y^{-1}) occurred from 2010 to 2015.

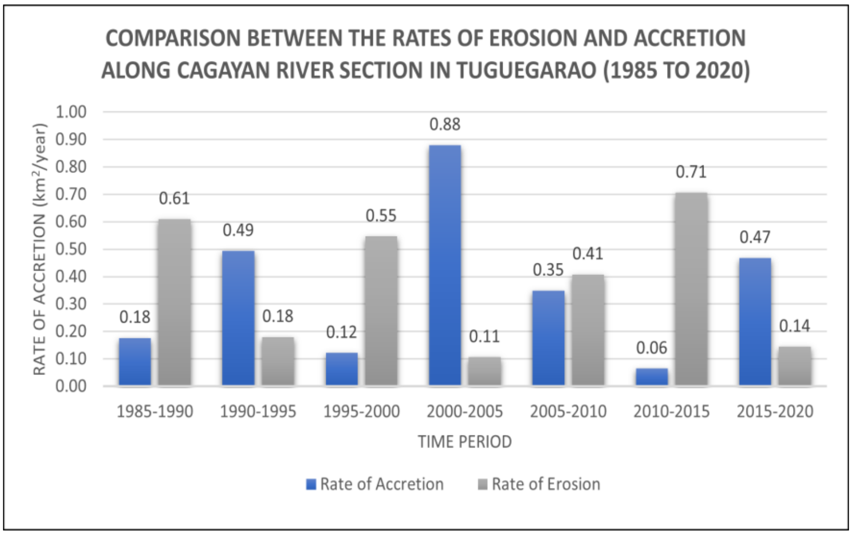


Figure 3.3 Comparison Between rates of Erosion and Accretion along Cagayan River Section in Tuguegarao City from 1985 to 2020.

Channel Pattern and Planform Morphological Changes

To verify adjustments in the river changes, one of the essential methods is by obtaining the geometric attributes of a river channel through spatial and temporal analysis. Actual meander bends are rarely symmetrical (Leopold and Langbein, 1966) and they consist of irregular bank lines. Table 2 shows the variations in channel length and valley length of the Cagayan River Section in Tuguegarao, and the amount of its bendiness is reflected through the sinuosity ratio. Figure III.1 shows an inverse relationship between the length of the channel to its valley. Over time, as the channel length increases, the valley distance decreases, and their difference is reflected in the channel sinuosity. The sinuosity of a river not only indicates the ratio between the channel length to its valley length, but also to the ratio between the valley slope to its channel slope. Increasing sinuosity over time (from 1.70 to 1.80) indicates a simultaneous growth in channel length, which causes the slope of the valley to lower. The lengthening of the channel occurs due to the versatility of the river to accommodate the change. However, the range of sinuosity values was maintained throughout the eight time periods between 1.70 and 1.80. The Cagayan River section in Tuguegarao is classified as an irregular meander according to Schumm (1963) as it has an average sinuosity (P) of 1.76, and a meandering channel according to Charlton (2007) having a sinuosity ratio of greater than 1.5.

Best fit circles were superimposed on the channel centerlines of the years 1985 and 2020 to illustrate the movement of the bank line. Figure III.5 shows the direction of movement of the meander and the changes in radius of curvatures (R_c). Bend 1 demonstrated that the meander moved in a southwest direction as shown by the black arrow, while Bend 2 shows that the meander moved in a northwest direction. The opposite directions of bend movement show the natural meandering process of a river. Fitting circles inside the bend allowed researchers to obtain the tightness of individual meander bends by measuring the radius of curvature. The centroid of the overlain circle represents the center of the bend, and the radius of curvature represents the radius of curvature of the meander bend. The radius of curvature of the Cagayan River Section at meander bend 1 remained at a steady pattern in contrast to meander bend 2 where the tightness of bend has continuously decreased over time. Also, it allowed researchers to measure the dimensions of meander wavelength and amplitude. Meander wavelength is the basic measurement in scaling the size of meander bends and meander amplitude is the measure of the cross-valley extensiveness. Individual meander bends have a measurement of half-wavelength. Both meander bends of the Cagayan River section appeared to have no significant change in their size and its trend has remained constant over the eight time periods. However, the extensiveness of both meanders is progressively growing through time. As bends evolve over time, meander amplitude is subject to increase and the radius of curvature tends to decrease.

Throughout the eight time periods, the size of the circles and its radius fitted on the meander bends on each of the centerline years gradually decreases. This occurrence suggests that the meander bends experienced contraction and where the deposition of sediment materials takes place. Comparison of the superimposed centerlines of individual years from 1985 to 2020 were also mapped to identify movement of centerline positions. Visual analysis was done to investigate the channel changes. Centerline movement during the eight time periods progresses towards the downstream of the valley (Figure 3.6). Movement along meander bend 1 grows towards southwest direction, whereas meander bend 2 grows towards northwest direction.

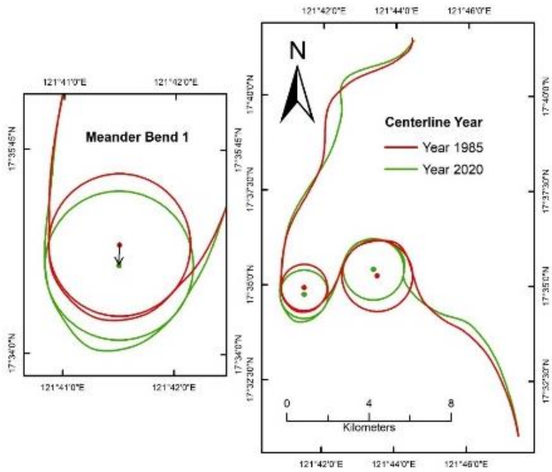


Figure 3.4. Fitted Circles of Known Radius of Curvature Along Cagayan River Section in Tuguegarao City (Years 1985 and 2020).

Extent and Magnitude of Lateral Migration

Channel migration analysis generally involves measurement of the lateral channel migration rate within the historical record. Lateral migration occurs as a result of formation of meanders and individual bends migrate, initiating erosion of the outer part of the concave bank and deposition on the inside bank. Channel migration rates are averaged over eight time periods from 1985 to 2020 (Table III-3). The highest rate of migration occurred between the years 2000 to 2005, having an 18.17 migration rate per year and the highest migration area was of the same time period. In contrast, migration rate and migration were relatively low between the years 1995 to 2000. Spatial analysis of migration movement revealed that the channel is gradually migrating especially along the meander bends. Figure III.6 shows the extent channel migration along the Cagayan River section in Tuguegarao City. Migration of meander bend 1 progressed in a southwest direction, while meander bend 2 progressed in a northwest direction.

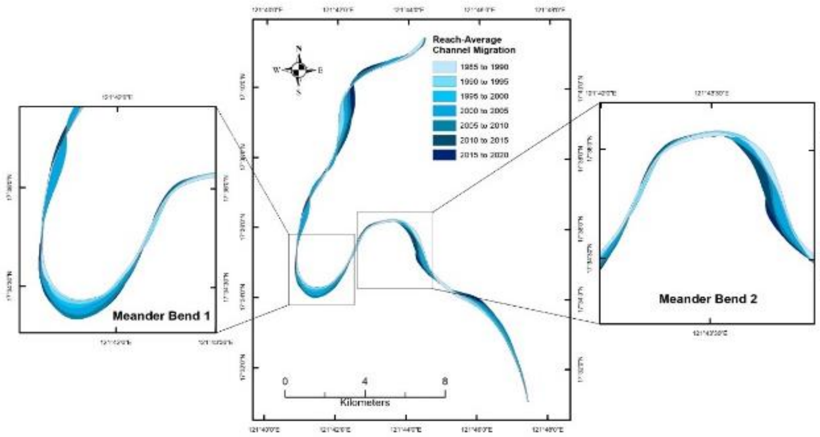


Figure 3.5. Extent of Channel Migration along the Cagayan River Section in Tuguegarao City from 1985 to 2020.

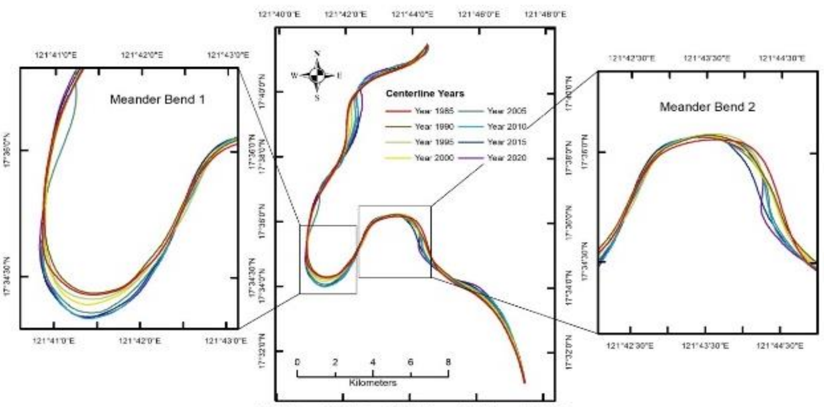


Figure 3.6. Historical Channel Centerline Positions of the Cagayan River Section in Tuguegarao City from 1985 to 2020.

Four modes of migration movement and combinations were modified by Lagasse et al. (2004) which was originated by Hooke (1977). To classify the mode of migration movement, initial and final centerline of meander bend are needed, as well as its geometric parameters such as the bend centroid, radius of the bend, and bend orientation. Extension and translation are measured from the bend centroid and seen as across-valley migration and down-valley migration, respectively; Expansion is determined through the increase or decrease in the bend radius; Rotation is the adjustment of the meander bend orientation with respect to the valley placement. Meander bend 1 of the Cagayan River section experienced extension as it migrated across the valley backed by channel lengthening and increasing amplitude. In contrast, meander bend 2 experienced translation as the migration moved down the valley. Any alterations in any of the said modes of movement results in a change in outer bank line location.

Erosion and Sediment Deposition

From 1985-2020, a total of 7.27 km^2 of land was accreted along the left bank compared to 6.77 km^2 of erosion. This means that during the past years, 0.50 km^2 of land has been gained along the left bank. In contrast, the right bank of the river section has a total of 5.58 km^2 of land that was accreted compared to 6.72 km^2 of erosion. This results in 1.24 km^2 of land being lost along the right bank. Based on Fig. III.8, vast amount of sediment deposition occurred on both the left and right banks of the channel during the period of 2000 to 2005. Deposition along the concave bends of the Cagayan River Section was supported by the continuous accumulation of sediments along the point bar. The immense amount of erosion is evident during the period of 2010 to 2015. The location of the greatest bank erosion within the bend changes over time as the bend grows and so does the principal direction of meander movement. Over the different time periods, the rate of accretion and erosion exceeds each other significantly. This suggests that rivers can undergo abrupt and dramatic alterations because of incidents like floods. However, erosion and accretion can also be brought on by land use management, flow disturbances and changes, and riparian vegetation. These reactions can be complicated, but in the absence of measures to slow erosion, most human influences increase erosion rates and can impair river channel stability for years. It has long been acknowledged that the primary process drivers responsible for channel migration and meander development were point bar construction and bank erosion.

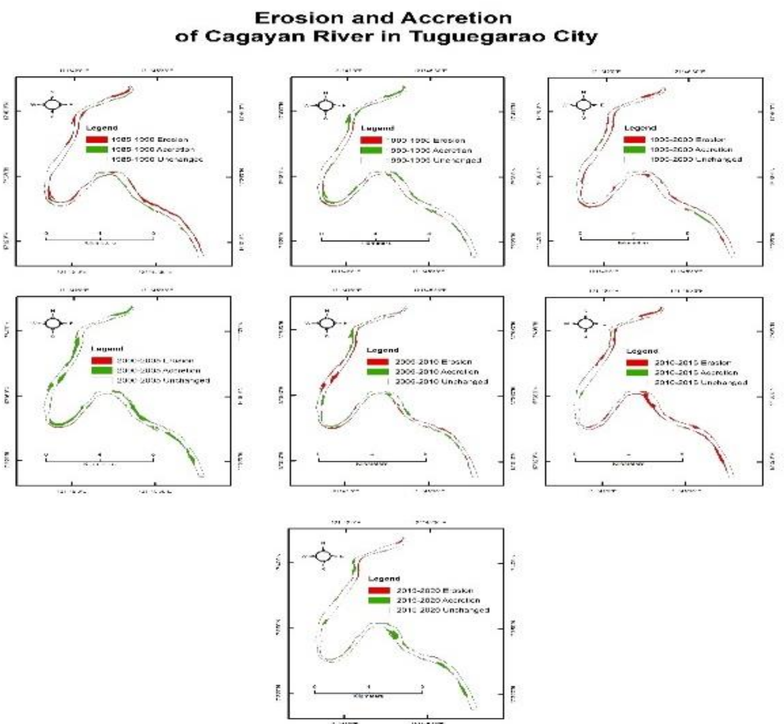


Figure 3 Error! No text of specified style in document.**.7. Areas of Erosion and Accretion along the Cagayan River Section in Tuguegarao City from 1985 to 2020.**

Anthropogenic Factors

With the help of Google Earth images, observations were made along the bank lines of both meander bends 1 and 2. Inspection showed that along the outer concave bank of the first meander bend, spur dike and revetment walls were constructed specifically towards the municipalities of Alibago and Enrile, respectively. Correspondingly, bank revetments were also seen along the outer bank of the second bend towards the municipality of Catagaman.

From 1990 to 2020, cultivated land and developed areas have expanded at the expense of vegetated areas across Tuguegarao, Solana and Enrile (Fig III.9). With large areas of agricultural land near the riverbank, an increase in sediment load can occur. This can be associated with the sandbars that have appeared across the river over the years. Also, high rates of erosion occurred along Tuguegarao after significant time intervals. It can be associated with the increase in developed areas near the river as it can result in an increase in surface run-off as surfaces become impermeable.

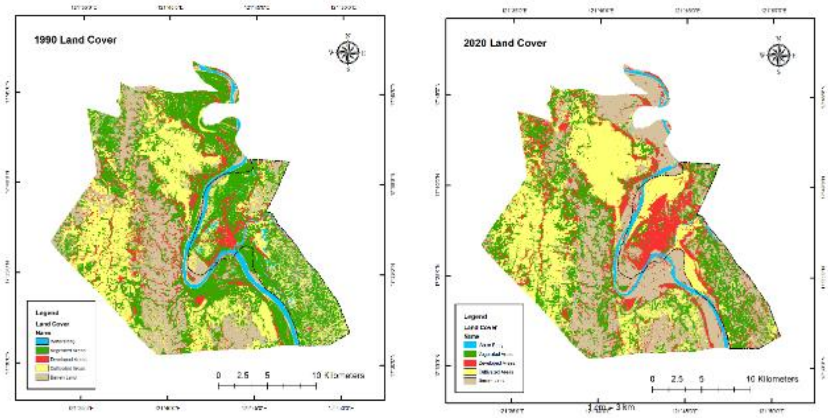


Figure 3.8. Land Cover Map of Tuguegarao, Enrile, and Solana (1990 and 2020)

CONCLUSION

The overall study intended to characterize, recognize, and understand the different morphological changes observed through spatial and temporal analysis by using a geomorphological approach and application of Remote sensing and GIS within the river boundary along the vicinity of Tuguegarao City, Cagayan. A combination of various techniques was used in order to identify changes in the morphology and such techniques were those mentioned by Hooke (1984) – bend parameters, curve fitting, spectral and graphical analysis, and classifications of change. Spatio-temporal analysis allowed the researchers to identify the changes occurring within a river system and how bends evolve through time. Channel lengthening, valley lowering, bendiness of meander bends, bankline movements, lateral shifts in channel migration, erosion detection, and sediment deposition are some of the principal modifications observed. Through systematic analysis, a wide range of controls were determined which influences meander growth, migration shifts, and erosion. It has long been acknowledged that the primary process drivers responsible for channel migration and meander development were point bar construction and bank erosion. Anthropogenic activities occurring both upstream and downstream of the channel can drastically impact the river. Any significant alterations in water discharge, sediment load, or bank stability due to natural or human events, can considerably influence the local rates of channel adjustments. Furthermore, the installation of river defenses such as construction of spur dikes and revetments along the riverbank may also be associated with the changes of the landscape along the river. Therefore, analysis of planform characteristics along with geomorphic activity can provide benefits in predictive spatial and temporal changes occurring within a river and give understanding of how the river system works of having the Passive Flood Barriers.

RECOMMENDATIONS

Further improvements can be made by associating hydrological, geotechnical, and sedimentological approaches within the study area as this alone does not account for the changes and adjustments in the river. Long-term flood data, discharge, and sediment load must also be taken into consideration. Since this study was done in the midst of the pandemic, conducting of fieldwork to gather data such as soil samples near the riverbed, obtaining rain gauge data, stream discharge data, and laboratory experiments can enhance the records and findings in this study.

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