



Past and future river bank trend assessment of lower Cagayan River, Philippines

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Received: 11 February 2023 / Accepted: 4 June 2024
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Abstract

In floodplain communities, river bank erosion is a catastrophic environmental hazard that can result in human migration and other consequences that could result in social, economic, and even health instability. Additionally, it may worsen the effects of flooding and related calamities. This study was conducted to investigate the spatial and temporal river bank changes of the Lower Cagayan River by assessing the current variability of the river channel in terms of erosion and accretion from 1991 to 2021 using Geographic Information System and Remote Sensing Techniques, in developing policy recommendations to address the adverse impacts of river erosion and accretion. It also utilizes the functionalities of the Digital Shoreline Analysis System in forecasting the future bank line positions for the next 10 and 20 years. Similarly, DSAS analysis revealed that the Left Bank has the highest erosion and accretion rate compared to the Right Bank. The River Bank Line Forecast estimated about 735.41 ha. Human settlements and infrastructure to be eroded in the next 20 years with corresponding uncertainty. Soil particle size distribution analysis indicates that the river banks are susceptible to erosion and have more than 95% of sand and silt content, and a very minimal portion of clay. The general findings of this study can serve as a basis for formulating policy recommendations and frameworks for more comprehensive riverbank restoration and rehabilitation projects and programs that integrate transdisciplinary principles of stream and floodplain restoration.

Keywords GEE · GIS and RS · DSAS · River bank · Erosion and accretion · LCR

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1 Introduction

Rivers are one of the most mysteriously magnificent natural features. It is unpredictable in nature and has touched a variety of societal systems from recreation to domestic, up to industrial purposes. As history suggests, human civilizations emerged in river valleys mainly for adequate water supply for irrigation, fertile soil, transportation, and fishing. The course of humanity was concurrently been shaped by river courses (Macklin & Lewin, 2020). Rivers, therefore, provide for humanity in various ways. It plays a significant role in community development from ancient times up to the age of today where a wealth of communities and human settlements are situated along the floodplain areas. The riparian habitat also serves the distinct purpose of supporting the aquatic and terrestrial flora and fauna. River channels host a huge collection of habitats and ecosystems that directly and indirectly benefit humans. Ecosystem services are also interconnected to river networks and by sustaining riparian and floodplain ecosystems that can provide provision for food, regulation of hazards, cultural identity and psychosocial development, and many more (Petsch et al., 2022). Thus, it is imperative for contemporary societies to devise sustainability frameworks that include river behavior and the changes that it undergoes over the course of time. The inspection of river landforms poses particular difficulties. It necessitates a planned, methodical approach due to the system complexity involved. River research has advanced to create the capacity to recognize, explore, and comprehend the continuity and connectedness of the flow patterns and fluvial features in a stream system (Hasanuzzaman & Mandal, 2020).

The dynamic nature of the river results in an alteration of its conventional course. Shifting of rivers has been observed all over the world concerning the susceptibility of adjacent communities. However, stream bank erosion is a natural process that may happen as a result of changes in flow regime and sediment supply, caused by factors like climate change or natural catchment disturbances. It is typically represented as a negative aspect of rivers (Hughes, 2016). Naturally, rivers shift course, meanders, and erode and deposit sediments. It is a natural process that benefits a wealth of biological and environmental ecosystems and organisms. This is not new, (Leopold & Langbein, 1966) emphasized that the remarkable geometric symmetry of rivers is not an outcome of chance. Meanders are the most likely shape that a river can assume since they appear to be how a river does the least work in turn. Arresting the river's natural course and halting its morphological change and shifting will stabilize its banks but will take a great toll on its aquatic and terrestrial biota. The unending cycles of erosion and alluvion in rivers are crucial for their vitality as old vegetation and landforms are being renewed. Recent advancements in river engineering and morphology have been employed to further understand river bank dynamics as a multi-variable function including channel hydraulics, geotechnical stability, biological components, and other parameters affecting bank retreat mechanisms (Zhao et al., 2022). Human activities contribute largely to modifying land use, flow hydraulics through river engineering structures, and river systems that increase flow velocity and discharge, which intensifies the possible bank erosion. These can alter the natural erosion amounts of a river system and can cause a direct effect on sediment inflow which can have a negative impact on riparian biodiversity that is highly dependent on river behavior, its morphology, and processes therewith (Sil et al., 2022). Bank erosion can violently happen in a greater magnitude on big rivers. Such devastating events often lead to injury, loss of life, community evacuation, and damage to property. The deposition of eroded earth and sediments greatly defines the amount of accretion that can occur. River accretion can take place on the river banks, or

it can be seen as new islands/bars are being formed. It also reduces the river depth which increases the potential of extreme weather events to ravage nearby communities with floods. River channel stability has long been the subject of river structure construction and conservation measures to restore and mitigate riverbank erosion that can affect riverine communities. Whereas, corresponding river and watershed rehabilitation programs have cost a fortune (Zaimes et al., 2019).

River biodiversity is negatively impacted by erosion and sediment deposition which has harmful impacts on aquatic plants and organisms (Mondal & Tripathy, 2020). Sediments from river bank erosion are made up of fine and coarse sediments. Fine sediments have been identified to have adverse impacts on lotic habitats in rivers and stream environments as they limit access to light and can cause wide-scale eutrophication in rivers by instigating high river water turbidity (Graf et al., 2016). It can also affect fishes as sediments in suspension can limit oxygen by limiting photosynthetic activities of aquatic plants, and other primary producers where other processes such as abrasion, clogging, burial, and other factors also induce impacts on aquatic vertebrate and different vertebrate and invertebrate species (Conroy et al., 2018). The ecological characteristics of fluvial environments are changed by excessive silt deposition, which also affects the health and balance of all biotic ecosystems (Ladrera et al., 2019). In this matter, land use and agriculture have a significant impact on the likelihood of surface runoff and soil erosion (Bekele, 2019; Borrelli et al., 2017). Sediments from eroded banks can easily be transported by flowing water that can smother river channels which can exacerbate extreme weather conditions such as heavy rainfall that can make floods and river bank erosion a devastating natural hazard in floodplain communities (Saikumar et al., 2022). At worst, river bank erosion can cause human displacement and other outcomes that can lead to social, economic, and health insecurity, and factors affecting overall human well-being (Saikia & Mahanta, 2023). Migration due to river bank erosion leaves families in great distress as elements such as livelihood and settlements may not be instantly present in migrated communities, let alone families (Kaiser, 2023; Rahman & Gain, 2020).

The list of possible causes and effects of river bank erosion and accretion can go on as there is an overlapping multi-disciplinary concern regarding the processes and their impact on systems. It has been a worldwide phenomenon where trade between human well-being and security and aquatic and riparian ecosystem sustainability is tearing the interest of experts (Thieme et al., 2021; Tickner et al., 2017). On the other hand, whichever side you into, a conservative assessment of river bank erosion and accretion factors and process is very inexplicable as there is only a handful, from the huge number of related studies that can be applied and adapted to a specific location as river morphology is affected by multiple different variables that may differ from other settings. The use of existing knowledge then still needs a thorough evaluation before being implemented. The indistinct characteristics of river systems make it a complex field of research as it demands a spatial and temporal set of data that can represent its system dynamics and processes for an accurate representation and results. Assessing and monitoring channel migration is essential for solving many geomorphic and riverbank resource constraints (Mohamad, et al., 2018). Conducting a river bank change assessment is highly dependent on historical data. A certain baseline must be set where the succeeding changes will be compared and quantified. GIS and Remote Sensing (RS) offers comprehensive and in-depth monitoring of natural geographic and surface changes of the earth. It has been widely used for a wide variety of applications, most of which include change detection and monitoring for natural resources such as land use and land cover changes, evapotranspiration, vegetation, and water body extraction

from satellites (Dan et al., 2020; Mashala et al., 2023; Monegaglia et al., 2018). Remotely sensed imagery has developed over the years and now provides fine-resolution data that can closely simulate physical processes without rigorous surveys and methods. It makes landscape assessment and monitoring more manageable even in large areas where the results of RS-based studies serve as a vital basis in decision-making for natural resources management (Langat et al., 2019). Moreover, RS is the only option to estimate and assess environmental, physical, and natural resource variations in other areas with immensely scarce or unavailable data (Avtar et al., 2020).

There has been a revolution in improving satellite imagery to be applied in a more detailed manner such as gridded precipitation, land use, and land cover, digital surface, elevation, terrain models, temperature imageries, and others. Satellite data has been extensively used together with cloud computing platforms and machine learning applications for diverse applications in modeling, mapping, agriculture, system analyses, risk and hazard assessment and management, meteorology, forecasting, change detection and monitoring, biodiversity, etc. (DeLancey et al., 2019; Cornejo-Bueno et al., 2019; Majidi Nezhad et al., 2021; Schwalbert et al., 2020). The humongous archive of datasets acquired by satellites that continuously navigate the Earth for years is constantly growing, and computer-based computing and processing software are somewhat incapable of handling such a vast amount of information. (Amani et al., 2020). Determining the actual spatial location of the river bank without prior knowledge of the study area may lead to inaccuracy and, hence, erroneous results. This concern has cascaded to concerned disciplines in physics and engineering to develop a method by which satellite imagery can be corrected to give satisfactory results. Such procedures include supervised classification, unsupervised classification, object-oriented classification, etc. These techniques revolve in a scheme that earth features have a corresponding reflectance to which the satellite sensors detected giving them unique pixel image values. Classification techniques aim to arrange like-features together to substantially enhance the way an image reflects features like water bodies, vegetation classes, and a lot more. Such techniques use assumptions and algorithms to successfully assign pixel values that would best represent a feature (Mehmood et al., 2022). However, the advent of cloud-based computing platforms has given way to more advanced environmental monitoring on a regional and planetary scale. Cloud-based computing engine uses algorithms to store, retrieve, process, and analyze data from a variety of remote-sensing products and applications. Google Earth Engine (GEE) is a publicly available data computing engine that archives petabyte-scale data of RS/satellite-derived products e.g. Landsat and MODIS, together with climate and geophysical datasets (Tamiminia et al., 2020). It is a user-driven computing platform that uses tools to process “big data” faster than traditional methods. It also has user interactive forums and a repository where codes and data management and processing procedures can be created, transferred, and shared between users. GEE has been employed in studies in agriculture, disaster management, earth and planetary sciences, land cover, vegetation mapping, and water resources monitoring (Mutanga & Kumar, 2019) as it allows for more strict spatiotemporal monitoring for better observation and analysis of systems.

The management of water and soil resources, hydro-technical projects, and various aspects of environmental protection all depend on understanding the mechanisms and rates of bank erosion, accretion, and lateral channel migration (Lovric & Totic, 2016). Several environmental, social, and design issues may arise as a result of bank erosion, including floodplains, agricultural, rural, and urban land erosion as well as damage to hydraulic structures and the transportation network (Billah et al., 2023). Also, the growth of riparian

vegetation flourishes as a result of bank accretion, and new alluvial land is gained that can be used for farming and livestock but by no means initially available as existing communities and livelihood may become under a series of changes as accretion of river banks incrementally take place (Mukherjee et al., 2017). In managing alluvial rivers, it is necessary to comprehend the nature of bank erosion and accretion as these may result in serious environmental and economic issues including land loss, threats to aquatic ecosystems, and damage to hydraulic structures like dams and abutments, it is crucial to be able to precisely anticipate the physical processes that cause riverbank erosion (Ercan & Younis, 2009). Since river bank erosion takes place unceasingly it contributes to the shifting of the river channel which can be distinctly observed through the migration of its bank line positions. River trend assessment provides significant insight into the mechanisms of river bank movement due to erosion and accretion. The need for river monitoring entails an acceptable procedure and advances in global observation systems and modeling based on probabilistic approaches enable a more comprehensive assessment of river bank dynamics. The Digital Shoreline Analysis System (DSAS), an open-sourced ArcGIS extension developed by USGS that operates based on a time series of vector shoreline locations, allows the user to compute rate-of-change statistics (Himmelstoss et al., 2021). The DSAS application was employed in this study to assess the riverbank shifting and movement of LCR (Mahmud et al., 2020; Mahmoodzada et al., 2019) can be used to calculate rates of change for any boundary-change problem that incorporates an identified feature position at discrete times, such as glacier limits, river banks, or land use/cover boundaries, even though the software's nomenclature is based on use in a coastal environment (Himmelstoss et al., 2021; Nhan et al., 2018). DSAS now leads an emerging trend of automated river bank monitoring as it has been applied in different settings with enough statistical tools and forecasting capability ideal for risk and hazard assessment due to changing river course (Bera & Maiti, 2019; Debnath et al., 2023). DSAS is coupled with multi-variable assessment (e.g. impact of land use change to river bank dynamics) and different vulnerability indices to produce a more explicit evaluation of possible hazards due to embankment breaching (Hasauzzaman et al., 2023).

(5) The Cagayan River is the longest river in the Philippines. Thousands of people take refuge along its floodplain for agriculture and settlements. Understanding the nature of LCR can give authorities a basis for how to improve riverbank structures by taking a closer look at the areas where bank failure often occurs. The urgency of the matter relies on the fact that the Cagayan River is also infamously known to have been the hotspot of flooding events in recent years due to immense typhoons that are presumed to be worsened by climate change that can alter the timing and pattern of river flow, particularly at its highest levels, which can lead to water-related catastrophes (Singson et al., 2023) This causes floodplain communities to incur losses in livelihood, life and property loss, health issues, etc. With the government on track to spend multi-billion pesos for river rehabilitation such as dredging, there should be a greater understanding of the nature of river planform and morphology to serve as a basis in strategically selecting the best measure and location to which restoration or mitigation measures should be employed. This study will do just that. As bank failures can occur in a short time or decade-long interval, this study can serve as a basis for assessing the possible anthropogenic factors that contribute to hastening the erosion and accretion process and to assess whether recent river infrastructure mitigates such events. To formulate effective recommendations for bank protection and DRRM measures, there is a need to understand the dynamics of shifting rivers not only in terms of their location but also in how they river bank migration claims river bank areas.

For this study, the primary focus is to determine the magnitude and severity of erosion and accretion and how it affects the river communities along the Lower Cagayan River (LCR). Since historical changes of river banks give us leeway to understand the dynamics of rivers. The objectives of this study are to: assess the river bank changes of LCR; predict the future river bankline position; assess the impacts of future changes to important economic activities and settlements; and develop policy recommendations to address the adverse impacts of river erosion and accretion. As a benchmarking study for river bank monitoring and assessment for the Cagayan River, this study is crucial in establishing research-based protocols for existing river engineering projects for disaster risk reduction and socio-economic interventions for possible affected communities which is made urgent by the foreseeable impacts of changing climate the different nexus connected.

2 Materials and methods

2.1 Study area

The area of focus of this study is the lower portion of the Cagayan River. The Towns around the LCR are the municipalities of Sta. Maria in Isabela where the most Upstream (UB) is located, and the municipalities of Enrile, Tuguegarao City, Solana, Iguig, Amulung, Alcala, Sto. Nino, Gattaran, Lasam, Lal-lo, Camalaniugan, and Aparri in Cagayan. For a more effective description of river bank erosion and accretion process and related factors, the LCR watershed (Fig. 1) was regarded in this study. The Cagayan River reaches inside the boundary town of Sta. Maria was considered. The overall length of the river considered in this study starts at $17^{\circ}30' 55''$ N; $121^{\circ} 47' 50''$ E up to the River Mouth in Aparri, Cagayan.

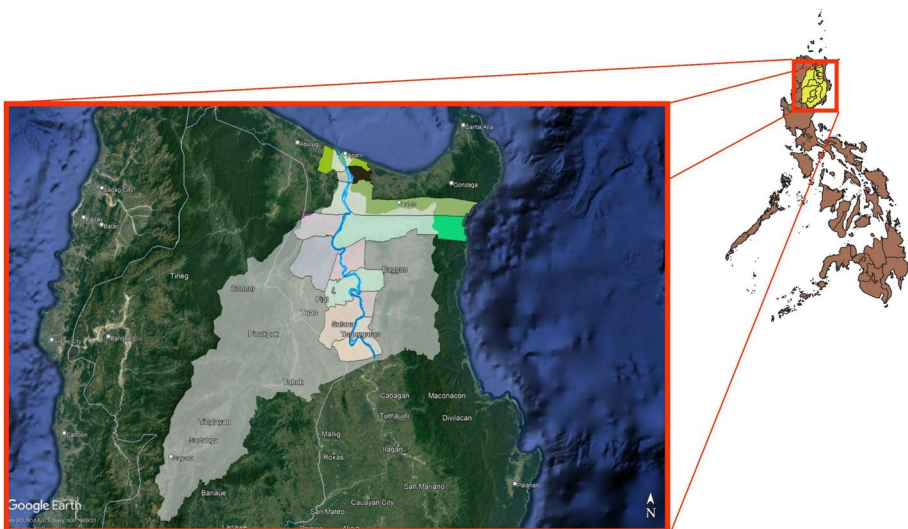


Fig. 1 The study area, highlighting the LCR and its basin

2.2 Data acquisition

2.2.1 Climatological and physical characterization of the study area

The prevailing climate was characterized using published reports mainly from the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), and other published articles. On the other hand, in collaboration with the Water Research and Development Center (WReDC) of Isabela State University, the soil type, land use/land cover, and digital elevation model (DEM) from the National Mapping and Resource Information Authority (NAMRIA) was utilized define the physical characteristics of the study area in terms of soil type, existing LULC, slope, and topography..

2.2.2 Landsat binary channel extraction

This study follows the workflow presented in Fig. 2. To assess and analyze river bank erosion and alluvion process for 30 years (1991–2021), the GEE code that was developed by (Boothroyd et al., 2020b) under Cagayan River Conditions when they demonstrated the application of GEE algorithms in extracting and the active binary channel was used. For further information about the processes’ framework, the reader is referred to (Boothroyd et al., 2020a, 2020b). The satellite data that were acquired using the GEE code makes use of Landsat data (Table 1) since it has a longer operation time that gives a more precise temporal analysis. Moreover, Landsat data has multi-spectral bands that can be combined and utilized for computing different indices that further distinguish the features of interest

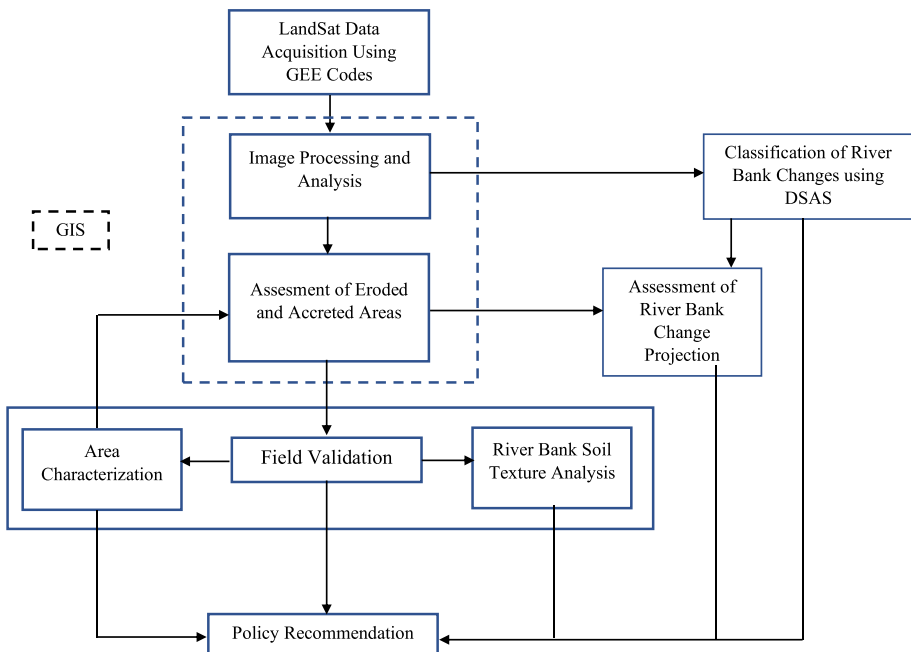


Fig. 2 Framework of the study

Table 1 Classification of input data

Type of data	Source	Resolution	Available range of data
Landsat 5 TM	USGS	30 m	1984–2012
Landsat 7 ETM+	USGS	30 m	1999–2021
Landsat 8 OLI/TIRS	USGS	30 m	2012–Present

for better data classification. Following the workflow of (Boothroyd et al., 2020b), the GEE code was configured to refer to the bank-full channel extension as the actual limits of the flowing river channel. It was done by utilizing all Landsat data that were corrected, compared, and filtered in terms of spectral reflectance between the acquisition under the specified period. A cloud masking procedure was also carried out using algorithms to minimize errors from cloud shadows. Based on the same study, temporal compositing forms a single image representation of temporal data within the timeframe. Indices to be solved using Landsat Images' multi-spectral bands such as Modified Normalized Difference Water Index (MNDWI), Normalized Difference Water Index (NDWI), Normalized Difference Vegetation Index, and Enhanced Vegetation Index (EVI) to accurately distinguish and classify wetted channels and alluvial deposits from other features. Then the resulting binary wetted channel and alluvial deposit were merged to define the active river channel. The succeeding conversion and extraction procedures to isolate the active river features to particularly define the river banks were done using GIS software.

2.3 Calculation of erosion and accretion areas from 1991 to 2021

Analytical research techniques were used in this investigation due to the study's attempt to determine the trends in river bank changes in terms of erosion, and alluvion (Ophra et al., 2018). After extracting the active LCR Channel from 1991 to 2021 the data processing and computation of the river erosion and accretion was performed using GIS Software. This study will account for the unchanged area for each period and follows the formula;

For erosion,

$$E = A_p - UA \quad (1)$$

where E is the bank erosion, A_p is the area of the previous year, and UA is the unchanged area.

For accretion,

$$Ac = A_N - UA \quad (2)$$

where Ac is the accretion area, A_N is the Area of the current year, and UA is the unchanged area.

The calculation of erosion rate in terms of m/yr was done for 2-year, 10-year, and 30-year periods. The difference between erosion and accretion values with respect to period is presented to further visualize the variability of the riverbank planform. Since this study mainly uses generated erosion and accretion maps to detect erosion and accretion cases, presenting it comprehensively and effectively is an essential process. And for more detailed visualization, the LCR has been divided into 4 sections namely, S1,

S2, S3, and S4 (Fig. 5). S1 is the upstream portion and the downstream section is S4. This was done to further emphasize the river bank changes attributed to the erosion and accretion process and the variations of the river's planform configuration over the years.

Furthermore, as a basis to represent the spatial distribution of erosion and accretion along the reach of the LCR, the baseline was drawn between the river outlet and the river upstream inlet. This serves as the baseline on which the distribution of erosion and accretion over the river reach will be computed.

2.4 River bank change analysis using DSAS

Following the DSAS 5.1 User Guide, baseline and shoreline data were prepared using the ArcGIS 10.8.1 environment. The attributes of the shapefiles representing the baseline, and shoreline data, which include riverbank historical locations, were set using an Attribute Automator. Then the default parameters were set for baseline, shoreline, and metadata. Any constant linear feature, such as the vegetation line, the high-water line, the low-water line, or the wet/dry line, can be used as a reference point for shoreline locations. On the other hand, all casted transects automatically placed by the DSAS program begin at the baseline, which is created by the user. In casting transects for calculation, the Cast Transect window then enables the exploration of options like maximum search distance, transect spacing, and smoothing distance. Each bank line is measured at the intersection of a transect and the rate of shoreline change is calculated using these measurement locations. Measured variations between shoreline locations over time serve as the foundation for each approach used to determine shoreline rates of change. The stated rates are measured along transects and given as meters of change per year (m/yr). The statistical parameters that DSAS uses include Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), Linear Regression Rate (LRR), Weighted Linear Regression (WLR), and other supplemental statistics. For this study, the river bank erosion and accretion rates were classified using EPR and LRR, which are given in terms of m/yr unit.

For complete and more comprehensive documentation of the DSAS process, the reader may refer to (Himmelstoss et al., 2021).

2.5 Assessment of the future morphological changes of LCR

The results of the GIS-based calculation and mapping of river bank erosion and accretion areas, and initial DSAS analysis in determining the corresponding rate of erosion and accretion along the length of the LCR were the basis of this assessment. This study utilizes the Kalman filter method that is embedded in the DSAS program in forecasting future river bank line locations for 10 and 20 years or 2032 and 2042. Kalman filter is a forecasting method based on the statistical values calculated using linear regression rate and end point rate method (Himmelstoss et al., 2021). This was particularly carried out since the subjective selection of critical areas may not result in a realistic estimation of future bank line position using simple linear regression. DSAS 5.0 Beta forecast technique more systematic statistical analysis and forecasting of the river bank

planform dynamics of the LCR. The GIS and DSAS results were compared to validate their respective results regarding the occurrence and presumptive estimation of the erosion and accretion values.

2.6 Study validation

2.6.1 Soil grain size distribution analysis

After generating the accreted and eroded areas along the river banks which were supplemented by the results of river bank classification using DSAS, erosion, and accretion samples were taken on the critical and accessible areas of the LCR on December 3, 2022. The soil samples were air-dried prior to analysis. Note that the lumps of soil were broken using mortar and pestle to account for the real particle sizes. The sieve analysis was conducted using the U.S.A. Standard Testing Sieve (ASTME-11 Specification). The particle size distribution of erosion and accretion soil samples was determined initially using sieve analysis for soil particles greater than 0.075 mm diameter (sieve #200). The sieve procedure was closely monitored to have the cumulative weight of sieved soil samples lower than 2% of the initial soil weight which is 500 g. For the particle size of soils that passed through the #200 sieve, a Hydrometer Analysis has been conducted (Bouyoucos, 1962). The hydrometer test uses Stoke's Law principle given by the formula;

$$v = \frac{\gamma_s - \gamma_w}{18\eta} D^2 \quad (3)$$

where:

v = velocity (cm/s).

γ_s = specific weight of soil solids (g/cm^3).

γ_w = unit weight of water (g/cm^3).

η = viscosity of water ($\text{g}\cdot\text{s}/\text{cm}^2$).

D = Diameter of soil Particle.

Here, the initial setup has the hydrometer in a floating position beyond the reading. 5 g of sodium hexametaphosphate (SHMP) solution was added for every 1000 ml of solution with a soil sample of ~ 50 g to maintain a density under 60 g which is the limit of the ASTM 152-H hydrometer. The meniscus and zero correction were determined from the control cylinder (1000 ml solution of distilled water and 5 g SHMP).

The soil samples were priorly soaked with SHMP solution for at least 20 min being stirred for 10 min. The soil slurry will then be transferred to a 1000 ml graduated cylinder. A wash bottle was used to wash in soil debris from every container and stirrer that will touch the soil slurry to minimize particle losses. The graduated cylinder was filled with distilled water up to the 1000 ml mark and was shaken for about 1 min. The hydrometer was placed carefully and successive readings were taken at 15 s, 30 s, 40 s, 1 min, 2 min, 4 min, 8 min, 15 min, 30 min, 1 h, 2 h, 4 h, and 8 h. Also, the corresponding temperature per reading was taken since hydrometer readings and calculations are highly dependent on temperature.

For the computational analysis, the soil particle distribution in terms of clay, sand, and silt percentage was determined using the method given by Gupta et al. (2021) and Das (2002).

3 Results and discussion

3.1 Physical and climatological characteristics of the study area

3.1.1 Rainfall and climate

The LCR is located in Cagayan Province and is classified under Type 3 Climate according to the Modified Corona Classification (Corporal-Lodangco & Leslie, 2017) where dry seasons span between one and three months from December to February or from March to May, and peak rainy seasons are not very noticeable. LCR is highly influenced by the seasonal patterns that affect the Philippines. The prevailing seasons in the country are associated with the Indian Ocean that transports moisture to the Indian subcontinent and Mainland Southeast Asia throughout the summer, it reaches the Philippines on its Southwest, thus, the Southwest Monsoon locally known as Habagat where heavy and extensive rainfall occurs as a result of air traveling over extensive expanses of warm tropical water. It is where typhoons and heavy rainfall are anticipated, Habagat brings excessive rainfall and powerful typhoons as early as June to Late October, which continues through early or even late November. Unlike the Habagat, Amihan (Northeast Monsoon) is distinguished by dry and cool weather as the wind from Siberia and China towards Southeast Asia (Clift et al., 2020; Cruz et al., 2013; Ganal, 2017). Forty-three percent (43%) of total the annual average rainfall in the country was accumulated during the Habagat Season. (Cruz et al., 2013) that cause intense rainfall and associated flooding to low-lying and downstream areas, however, it must be recognized that in these extreme climatic and weather events, the tropical cyclones were not the primary cause of the excessive rainfall; rather, the Habagat's phenomenon was exacerbated by the presence of tropical cyclones to the north and northeast of Luzon. (Cayanan et al., 2011). The Cagayan province has an annual mean precipitation of 175.33 mm, having November as the wettest and March as the driest month. It is also one of the most affected provinces in terms of natural meteorological disasters. Such as tropical cyclones (PAGASA, 2018; PAGASA, 2019). These cyclones have caused massive inundation and associated calamities downstream which affected thousands of families e.g. Typhoon Ulysses in 2020, one of the most devastating Super Typhoons ever recorded to date struck the region with an immense ferocity that submerged the Cagayan River Floodplains downstream.

3.1.2 Slope and topography

When analyzing hydrological processes at various geographical and temporal dimensions, topographic aspects are of high concern. Topographic elements have impacts on hydrological processes including the slope's length, altitude variation, and form. The runoff start threshold, peak duration, concentration time, flow volume and intensity, and erosion power fluctuations are all strongly influenced by the slope's shape and growth direction. Topography and other related information also have a role in the accuracy and effectiveness of the numerous soil erosion models that have been created. (Kiani-Harchegani et al., 2022). The LCR is the downstream portion of the great Cagayan River. It is situated at the valley

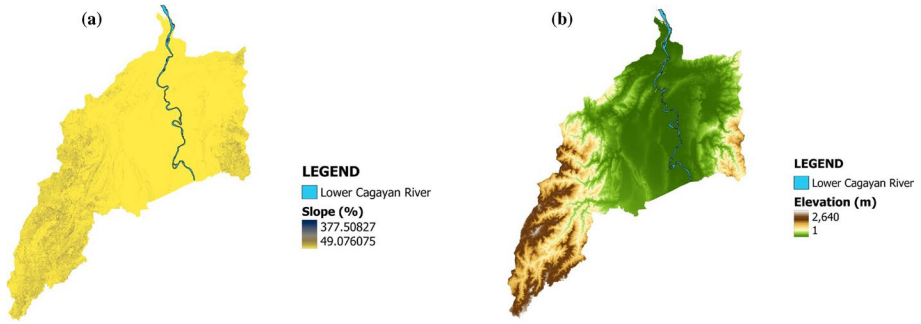


Fig. 3 Slope and elevation map of LCR a slope map b elevation map

floor where it accumulates lateral inflow from overland flow rushing down from its flood plain. The slope map of CRB (Fig. 3) is shown since water from the upstream as influenced by the topography flows towards the upper Cagayan River which will then flow as LCR. The minimum slope along the LCR (Fig. 3a) is at 0–7° (degree inclination) where the high elevation areas range from 15 to 77.75° inclination. Figure 3b also implies that the valley area and the floodplain of the LCR area have low elevations.

3.1.3 Soil type and land use

The LCR soil type is presented in Fig. 4a. Soil erosion is found to be more prevalent in sandy loam soils, compared to clay and clay loam soils (Ekwue & Harrilal, 2010). The soil type in the meandering portions of the LCR is predominantly a variation of silty loam or sandy loam. Clayey soil types are also present along the river channel but are more reflected on the floodplain. River menders may also be associated with the corresponding soil type that governs the river channel. For example, the river channels dominated by clay soil type are not as sinuous as the other parts. Similarly, the land use and land cover of the area also have a consequential impact on the overall hydrology and watershed process that induced relative impacts on runoff, surface erosion, streamflow, and river bank properties. The frequency of floods and river bank erosion is significantly correlated with land use change, both of which have severe ramifications. Cropland and human settlements are

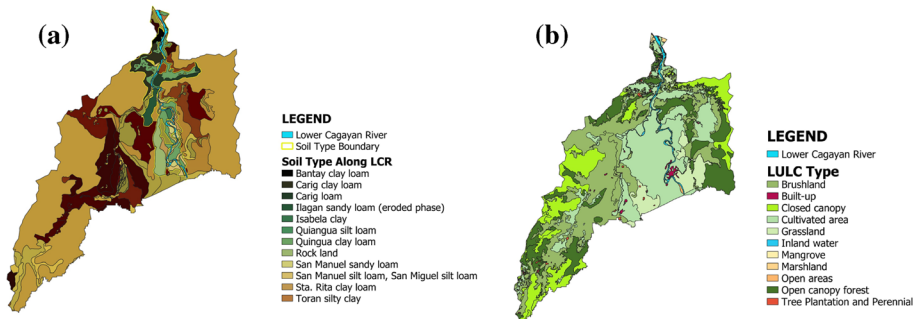


Fig. 4 Soil type and land cover map of LCR basin. a Soil type b land cover

considered to be flood-prone areas (Kometa et al., 2021). Figure 4b shows that annual crop primarily dominates the LCR floodplains particularly, corn monoculture but with considerable crop diversity. There is a close-pack community displayed by the built-up or settlement areas near the river banks and over the floodplains, just along the riparian margin. Grassland and shrubs are also prominent in the area. The absence of plant cover drastically affects the way soils from adjacent riverine lands are being easily washed away into rivers. Crop fields and pastures are frequently created on land that was formerly a forest or another type of natural environment, including floodplains and wetlands. With these factors considered, the floodplain of LCR is predominantly classified as annual crop/vegetation.

3.2 Calculation of erosion and accretion areas

The calculation of erosion and accretion areas was carried out using GIS software. Table 2 shows the erosion and accretion areas per time period. The estimated erosion area from 1997 to 1999 appears to be the lowest of all at -96.59 ha/2-yr or -46.29 ha/yr which is lower than the 30-year annual average of 75.86 ha/yr (2276.40 ha/30-yr). On the other hand, erosion values for where the total eroded area is just shy of reaching over -400 ha per/2-yr at -384.2 ha, All periods except excluding the 1997–1999 and the 2007–2009 periods have computed river bank eroded area more than -400 ha/2-yr or -200 ha/year whereas the highest eroded area was calculated to be on 2001–2003, and 2011–2013

Table 2 Calculated erosion and accretion values

Period	Erosion, ha	Accretion, ha	Unchanged area, ha
2 year			
1991–1993	-675.54	456.52	7420.866
1993–1995	-513.59	451.90	7363.795
1995–1997	-450.75	499.46	7364.951
1997–1999	-96.59	635.03	7767.821
1999–2001	-424.49	261.34	7978.36
2001–2003	-732.48	179.03	7507.215
2003–2005	-442.83	830.44	7243.413
2005–2007	-498.81	820.50	7575.041
2007–2009	-384.20	507.61	8011.343
2009–2011	-450.93	186.77	8068.028
2011–2013	-761.29	651.60	7493.514
2013–2015	-648.55	209.55	7496.568
2015–2017	-196.11	818.19	7510.004
2017–2019	-384.27	257.22	7943.925
2019–2021	-288.03	880.62	7913.119
10 year			
1991–2001	-1320.41	1177.12	6919.284
2001–2011	-1318.38	1303.27	6936.42
2011–2021	-1696.32	1157.39	7097.411
30 year			
1991–2021	-2973.73	2276.40	5820.007

The negative dimension was adapted for erosion values and no sign of accretion

periods, where more than -350 ha/year of bank erosion was computed at -732.48 ha/2-yr and -761.29 ha/2-yr, respectively, which is seen to happen after 10 years. It is also worth noting that in 2015–2017, 2017–2019, and 2019–2022 periods, the total erosion areas decreased by -196.11 ha/2-yr, -384.27 ha/2-yr, and -288.03 ha/2-yr, respectively. Moreover, the 30-year total eroded and accreted river bank areas were -2973.7 and 2276.4 ha, respectively.

To strategically reflect the spatial process of erosion and accretion along the stretch of the LCR, a 10-km interval transect was created and the amount of erosion between the

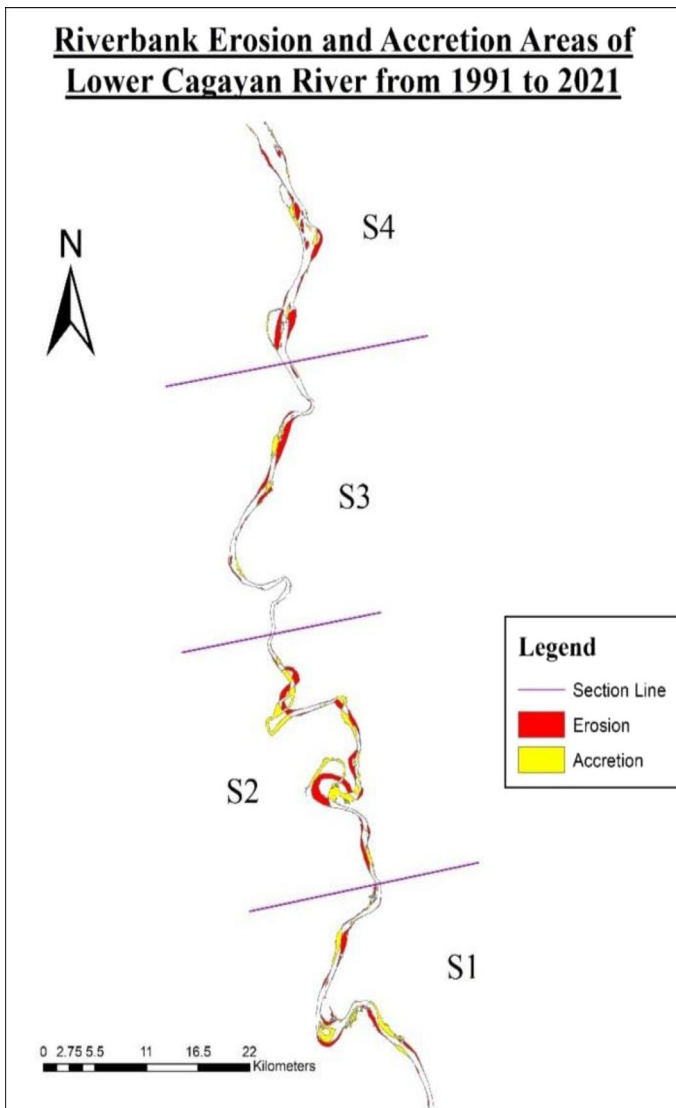


Fig. 5 30 year riverbank erosion and accretion areas along the LCR

transects was calculated. The area of sediment accumulation that modifies the river bank by accretion was estimated to be higher than the erosion area over a 30-year period (Fig. 5). This trend is also observed in the 10-year period. In terms of erosion, the river bank has undergone significant changes S2 has a more noticeable morphological change in terms of how the river bank shifts and meanders where 1226.41 ha of the total erosion took place in this area for the past 30 years. Whereas, S4 has accumulated a total eroded river bank area of 760.31 ha, 529.61 for S3, and 557.39 for S1, successively. Subsequently, the 30-yr accretion value for S1 is 663.98 ha, 1113.42 ha. for S2, 214.82 ha. for S3, and 284.18 ha. for S4. In terms of accretion values from 1991 to 2001, S2 has the highest accreted river bank area at 203.75 ha, followed by S4, at 144.44 ha. Simultaneously, S3 and S1 account for 73.71 ha and 55.33 ha of river bank accretion, respectively. In reference to the unchanged area, the 2-year period reveals a greater extent of unchanged river channel area (river channel width inside the bounds of the river bank lines) over the 10-year compared the 30-year period (Table 2). This implies that the interval of consideration gives a more refined inspection of the temporal changes in river planform, which for this study, is more focused on the bank line dynamics. 2007–2009, and 2009–2011, periods have recorded the highest unchanged area at 8011.34 ha and 8068.03 ha, respectively. In contrast, the 10-year and 30-year periods were estimated to have an unchanged below 7000 ha, except for the 2011–2021 period. These results, however, only suggest that over a longer course of time, the eroded and accreted areas are continuously getting replenished and modified by the continuous processes that drive erosion and accretion. Also, in the long run, an intense erosion process that happens in a short increment of time can be inconsequential to parameters such as total erosion rate. If a considerable erosion happens to the river bank that has been priorly accreted, the extent of erosion, though higher than a certain erosion that has occurred along the natural river bank where the real river topography was taken, can be considered to be less pronounced since the material that was eroded was a product of sediment deposition which is a layer that protects the original river bank materials. In socioeconomic terms, the severity of erosion can be made synonymous with the degree of the potential damage it can impose on existing activities along the river banks due to soil and property loss. However, this study is confined to a change of river bank position.

3.3 Spatial distribution of erosion and accretion along the LCR

The spatial distribution of erosion and accretion for 1991–2001, 2001–2011, and 2011–2021 (Table 2) shows that there is a pattern wherein as the erosion process increases, a considerable increase in accretion is also observed. The river flows from the Enrile-Sta. Maria's UB (starting point of measurement) towards the river mouth at Aparri, Cagayan. An increase in river bank sediment deposition and erosion took place at S2 where the calculated highest eroded and accreted area, of 316.654 ha and 372.034 ha, respectively, and is found to have occurred between 25 and 35 km from the UB, then diminishes upon approaching S3 at 55–65 km distance from the UB, then diminishes upon approaching S3 at 55–65 km distance from the UB. An increment in both erosion and accretion is also observed, approaching the river mouth. It is also important to point out that based on the spatial distribution of accretion and erosion along the river channel, and the generated erosion and accretion map, the spikes in erosion values occur at the meandering portions of the river. This may be attributed to the force of water that pushes towards the outer bends as water flows downstream. The velocity of flowing water can greatly affect the detachment

of soil materials along meandering river banks since the abrasion, hydraulic action, and deeper plunge pools are produced because a meander's increased water velocity also promotes a larger scouring impact on the river bank material. In addition to the varying river characteristics such as riparian vegetation, morphology, geology, and floodplain condition. According to the findings of (Konsoer et al., 2016), local bank properties have a significant impact on erosion rates and bank retreat processes changes in the long-term patterns and trends of migration of channels. Upon examining the spatial distribution of the 10-year periods, the similarity of the distribution pattern is distinct in terms of the occurrence of the highest erosion value within S2 where the most complex meanders of the LCR are located. The 10-year erosion and accretion values with respect to distance were estimated. The highest erosion during the 1991–2001 period occur at S2 between 25 and 35 from the UB. For 2001–2011 the highest computed river bank eroded area of -274.025 ha occurred at S2, 25 km to 35 km distance from the UB, and the highest accreted area of 372.50 ha was also found in S2, between 35 and 45 km distance from the UB. The case is the same for the 2011–2021 period since the highest eroded area of 410.257 ha, and the highest accreted area of 244.662 is found between is also located between 25 and 35 km from the UB, which is situated at S2.

The placement of the baselines for computation and the designation of distance interval was done to further quantitatively portray the severity of erosion in terms of magnitude in a specific location. It may be subjective in nature but it is based upon the prior evaluation of the generated maps that portray the location of eroded and eroded areas along the bank lines. Exhibiting it together with the generated maps based on historical data analysis serves a consequential part in defining the extent of river bank changes due to erosion and accretion. The total erosion for the 1991–2001, 2001–2011, and 2011–2021 periods has an area of -1307.68 ha, -1301.92 ha, and -1677.6 ha, respectively, with a standard deviation (SD) of 215 ha. And accretion values of 1160.53 ha, 1288.71 ha, and 1143.63 ha, respectively, with a corresponding SD of 79.33 ha. The standard deviation simply measures the average level of variability of the data. It indicates the average deviation of each value from the mean, which is, in this case, $\frac{-1429.04 \text{ ha-erosion}}{\text{decade}}$, and $\frac{1197 \text{ ha-accretion}}{\text{decade}}$. On the other hand, a more pronounced erosion and accretion were generated by taking the 30-yr temporal data. Note that the decadal erosion and accretion average derived from the 30-yr period is different from taking the mean of a 10-yr period data, since the river bank baseline from 1991 is the only basis for computation, unlike the latter that uses 1991, 2001, and 2011 as a baseline for every 10-year increment. Though different in nature, the value generated from evaluating the 10-yr period gives the potential to distinguish river bank change from one timeframe to another, where parameters can be incorporated to deduce the vital cause of disparity of erosion and accretion for every period.

Figure 6 gives the overall spatial distribution of erosion and accretion along the river banks of LCR. It still carries the same attributes from 10-yr period where the critical erosion and accretion values are still located at S2. The highest erosion value for a 30-yr time span happened between 25 and 35 m from the UB, having a total eroded area of -640.25 ha. The highest computed accretion value of 565.5 ha, took place between 35 and 45 km from the UB. The total accumulated erosion and accretion for 30 years are -2940.535 ha and 2147.920 ha, respectively (Table 3). This includes the river bank variations when along the course of time, the initial area gets eroded and accreted afterward or vice versa, allowing distinct locations to experience continuous erosion and accretion which assort them to be more critical in nature.

Spatial Distribution of Erosion and Accretion Along Lower Cagayan River Basin from 1991-2021

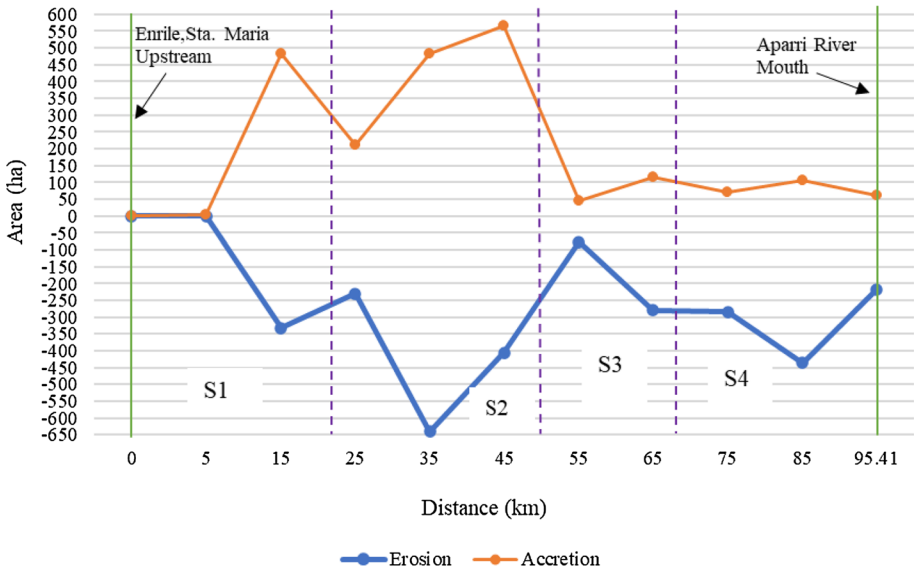


Fig. 6 Spatial distribution of erosion and accretion along lower Cagayan River basin from 1991 to 2021

Table 3 30 year erosion and accretion value with respect to distance from 1991 to 2021

Cumulative distance (km)	Erosion (ha)	Accretion (ha)
0–5	– 38.494	3.736
5–15	– 331.793	483.462
15–25	– 230.144	211.289
25–35	– 640.252	483.858
35–45	– 404.965	565.500
45–55	– 77.464	45.038
55–65	– 280.207	116.470
65–75	– 283.740	69.332
75–85	– 436.469	106.840
95–95.41	– 217.008	62.396
SUM	– 2940.535	2147.920

The negative dimension was adapted for erosion values and a positive dimension for accretion

Figure 6 further emphasizes the variability of erosion and accretion between 1991 and 2021. The spatio-temporal variation in the extent of erosion is crucial in defining the river bank activity. The biannual erosion and accretion values (Table 4) show no correlation with time. Nonetheless, a careful assessment of the spatiotemporal erosion-accretion patterns shows that while erosion and alluvion happen simultaneously at any period, it is the rate

Table 4 Biannual erosion and accretion values from 1991 to 2021

Year	Erosion (ha)	Accretion (ha)
1991–1993	675.54	456.52
1993–1995	513.59	451.90
1995–1997	450.75	499.46
1997–1999	96.59	635.03
1999–2001	424.49	261.34
2001–2003	732.48	179.03
2003–2005	442.83	830.44
2005–2007	498.81	820.50
2007–2009	384.20	507.61
2009–2011	450.93	186.77
2011–2013	761.29	651.60
2013–2015	648.55	209.55
2015–2017	196.11	818.19
2017–2019	384.27	257.22
2019–2021	288.03	880.62

The negative dimension was adapted for erosion values and a positive dimension for accretion

or corresponding magnitude that makes the other process more dominant than the other. This was expounded in Fig. 6. Using the value of eroded area along the LCR river banks, the 1991–1993 period shows a greater erosion process. As time progresses, a shift in terms of accretion is a more dominant process to be then followed subsequently by the other process. It somehow is impractical to assume that erosion and accretion are inversely proportional to each other. By considering relevant facts such as the connection of sedimentation to erosion, and to accretion, the far-fetch option of directly relating two parameters by mere observation is not an acceptable basis. Bank erosion greatly contributes to sedimentation in streams, rivers, and other waterways (Cashman et al., 2018; Hayes et al., 2023) these sediments are carried by the flowing water, which will then be deposited, mostly on the inside banks of the river, since water velocity decreases as it losses energy when it comes into contact to the shallow portions of the river, it losses sediments in the process. The sediment accumulation along river banks and adjacent floodplains is called accretion. Based on this, the increase in erosion values over time can be associated with the delay that the sediments from an erosion that has occurred upstream, reach the accretion locations. In combination with the detached soil debris that originated from soil erosion on the floodplains that was discharged to the river, adding up to its total sediment load to be deposited by the river as accretion. This also explains why both erosion and accretion process, has patterns that are somewhat dependent on each other in hindsight. However, this explanation is rather too simple than complete. From the figure alone, between 2009 and 2015 both erosion and accretion values are observed to have an incremental action. Also, from Fig. 7, it is more pronounced that there has been a rising accretion trend for the past 5 years (since 2015), where the amount of accretion extent is way higher than erosion (Table 4).

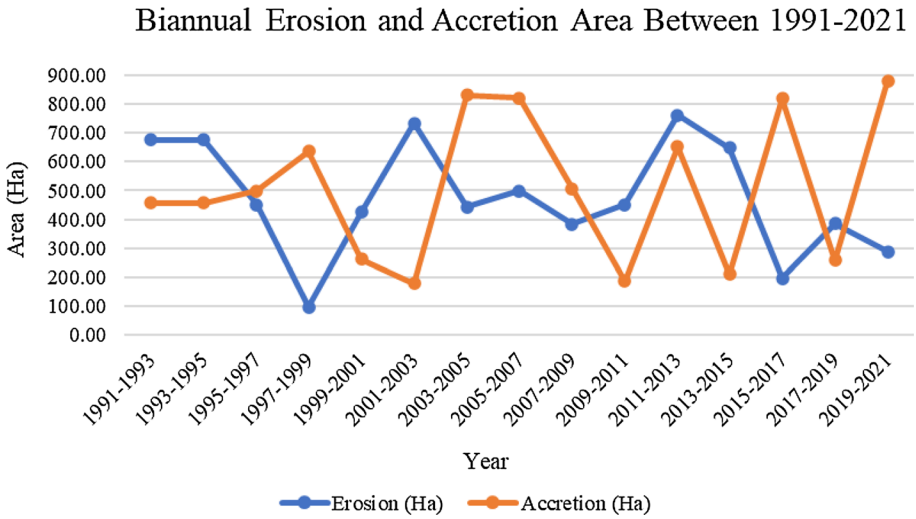


Fig. 7 Variability of erosion and accretion areas between 1991 and 2021

3.4 River bank change analysis using DSAS

3.4.1 Classification of river bank changes DSAS

The rate of change of the LCR bank lines was calculated using the linear regression rate (LRR) by applying the least squares regression line to the river bank locations marked by the transect lines and based on the distance difference; End Point Rate (EPR) which

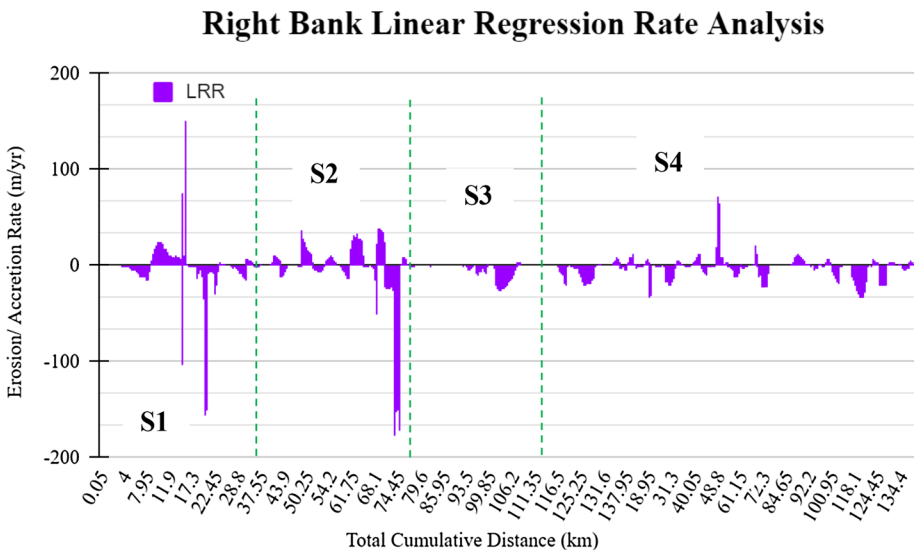


Fig. 8 Right bank linear regression rate analysis using DSAS

calculates the rate of change from the baseline year's river bank position to the river bank's most recent location.

3.4.2 Right bank change analysis

Figure 8 shows the corresponding erosion rate derived using LRR Analysis with 2806 transects with 50 m spacing. The calculated maximum erosion rate is -176.74 , which also implies that 66.54% of the total transects cast were classified as erosional where 45.83% have statistically significant erosion. On the contrary, the generated maximum accretion rate is 150.16 m/yr where 939 of the total transects are accretional which means 33.46% of the total bank line transects have accretional characteristics where 21.35% have statistically significant accretion. From the generated results, the LRR also shows that the total right bank change for the past 30 years has been dominated by erosion having an average river bank erosion activity of -1.78 m/yr, having an average erosion and accretion value of -6.51 and 7.62 m/yr, respectively. Figure 8 depicts the spatial erosion rate in terms of linear distance of erosion or accretion per year of the river, but this time, the length of the right bank was considered to be approximately 146.5 km which was estimated from the spacing and the number of the transect lines. From the End Point Rate Analysis (Fig. 9), 65.54% were identified as erosional, and of those, 49.04% had statistically significant erosion and the maximum erosion rate, which was found to be higher than the LRR is -231.28 m/yr. The produced EPR maximum accretion rate is 202.5 m/yr, which is lower than the LRR value since 35.46% of the total bank line transects exhibit accretional features whereas 27.6% showed statistically significant accretion. EPR also suggests that the erosion process is the dominant process having a right bank rate of change of -1.3 m/yr from 1991 to 2021.

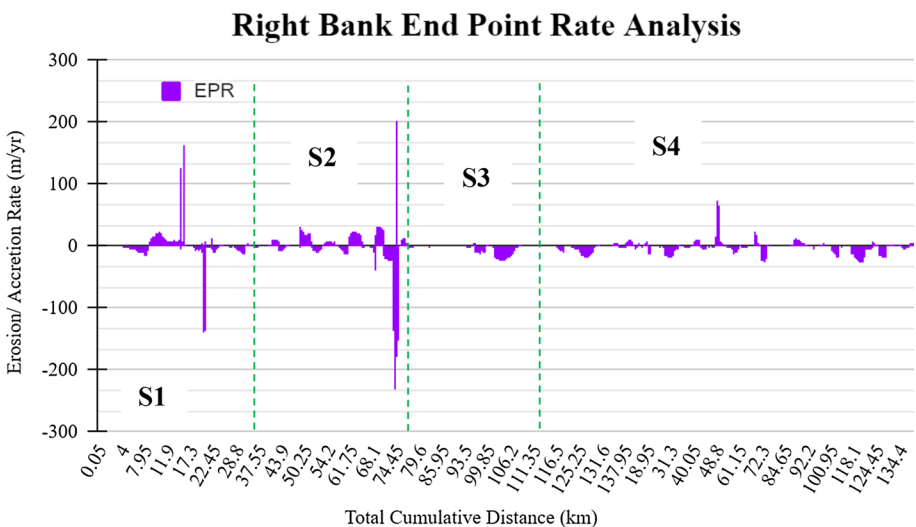


Fig. 9 Right bank end point rate analysis using DSAS

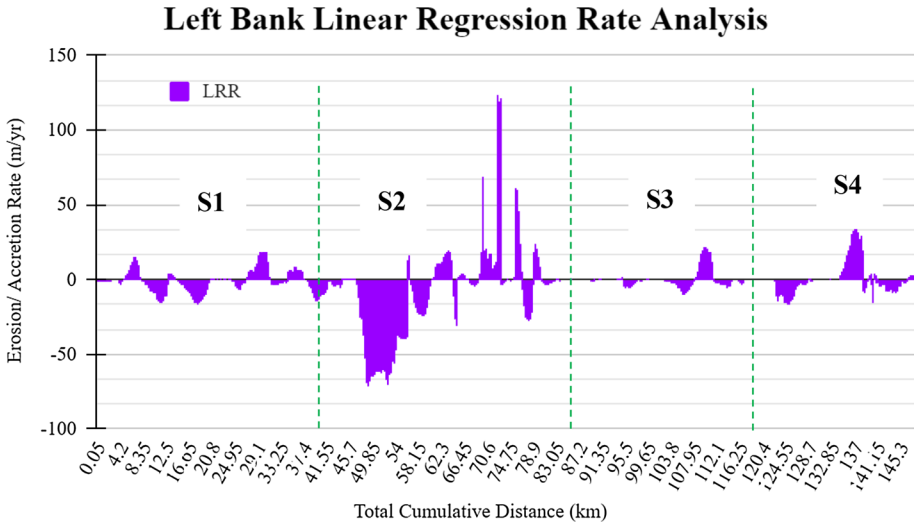


Fig. 10 Left bank linear regression rate analysis using DSAS

3.4.3 Left bank change analysis

The left river bank analysis showed a more pronounced river bank modification due to erosion and accretion (Fig. 10). The Left bank erosion and accretion rate were computed at 2956 transect lines cast along the estimated 147.85-km extent of the LCR Left Bank. LRR analysis implies that the planform changes on the Left bank are dominated by the erosion process having an average bank line variation of -2.18 m/yr from 1991 to 2021 (Fig. 5).

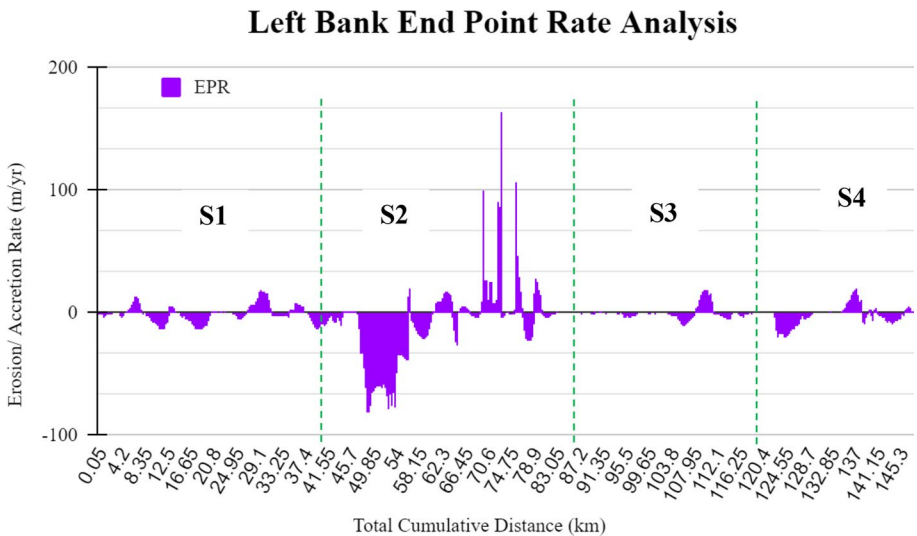


Fig. 11 Left bank end point rate analysis using DSAS

The analysis shows that 68.44% of the transects were erosional and 54.36% has statistically significant erosion values. From this, the resulting erosion rate is -11.05 m/yr with a maximum erosion value of -71.91 m/yr at about 49 km from the UB. Meanwhile, from 31.56% of the accretional transect, 22.19% of which has a statistically significant erosion where the Left bank is identified to have a sediment deposition rate of 9.79 m/yr.

Likewise, the EPR erosion rate (Fig. 11) also suggests that the dominant river bank change is erosion, which quantifies an average bank line change of -3.56 m/yr from 1991 to 2021. The erosion rate of the Left bank was computed using a total of 2956 transect lines where 71.62% are erosional, and 57.92% have statistically significant erosion. The resulting average erosion rate is -8.52 m/yr with a maximum erosion rate value of -82.08 m/yr. In addition, the corresponding accretion rate was estimated to be at 8.96 m/yr. with a maximum accretion rate value of 163.51 m/yr. This was computed using the 839 accretional transects where 21.71% have statistically significant accretional characteristics.

From the results of the DSAS analysis, the river bank areas along the meanders at S2 possess the highest variability in terms of bank line dynamics. Also, the initial detection (Fig. 5) or the erosion and accretion locations that were identified to take place more frequently along the meander bends, where the sediment gets deposited along the inside bends and the outer bank lines experience erosional activities. Table 5 shows that EPR values for the average erosion rates are lower yet comparable to LRR values where both give a satisfactory estimation of the river bank dynamics using 30-yr historical bank line position data. However, a significant discrepancy arises when considering the minimum and maximum erosion and accretion rates which may arise from the theory governing both analyses. EPR is sensitive to outliers particularly when the shoreline change does not follow a linear scheme. LRR on the other hand, captures all available transects making it more robust in dealing with outliers. Nevertheless, both methods are simultaneously being used in river bank migration studies (Bhuyan et al., 2023).

3.5 Assessment of the future morphological changes of LCR

The Kalman filter runs an analysis whenever a shoreline observation is made to reduce the difference between the predicted and observed shoreline positions. This analysis also includes updating the rate and uncertainty (Long & Plant, 2012; Himmelstoss et al., 2021).

Figures 12 and 13 show the forecasted LCR bank line for the next 10 and 20 years with respect to the river bank line position in 2021. Moreover, it appears that for the results of the future river bank position, the S2 section is expected to undergo rigorous bank line shifting along its meander bends. The predicted 10-yr and 20-yr bank line position at the randomly selected point of measurement where erosion and accretion values are expected

Table 5 Erosion and accretion rate summary of LCR

River bank change analysis	Right bank		Left bank	
	LRR (m/yr)	EPR (m/yr)	LRR (m/yr)	EPR (m/yr)
Average erosion rate	-6.51	-5.77	-8.61	-8.52
Average accretion rate	7.62	7.18	-9.79	8.96
Maximum erosion rate	-176.74	-231.28	-71.91	-82.08
Maximum accretion rate	150.16	202.5	123.33	163.51

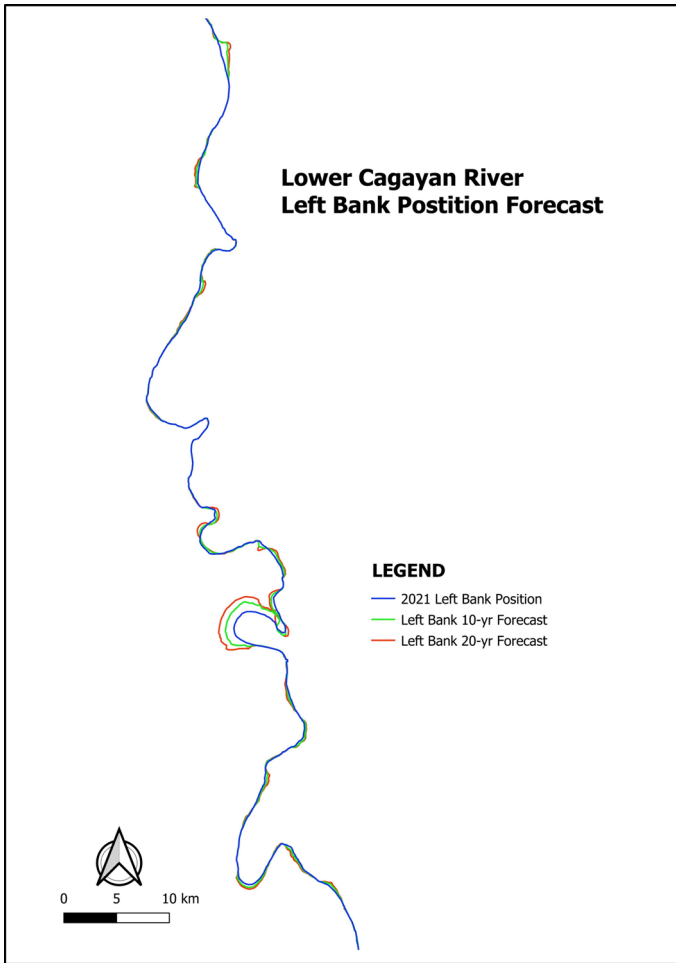


Fig. 12 LCR right bank position forecast

to double after 10 years on 2021 and 2031, respectively. In addition, the river bank dynamics of the Left bank are more apparent in comparison with the right bank.

3.6 Soil grain size distribution analysis

The particle sizes of the river bank soil samples were gathered to give deeper insight into the mechanical aspect of soil that is important in determining the soil characteristics that can be related to how well it can resist erosion-inducing factors such as high-velocity channel flows that can cause bank failure if the shear strength of the river bank is unable to withstand the water pressure, as well as the soil attributes that dictate soil consistency, or the soil's ability to band together.

The critical erosion areas were generated using GIS analysis and DSAS, but one of the constraints of this study is the accessibility of the identified river banks for soil sampling

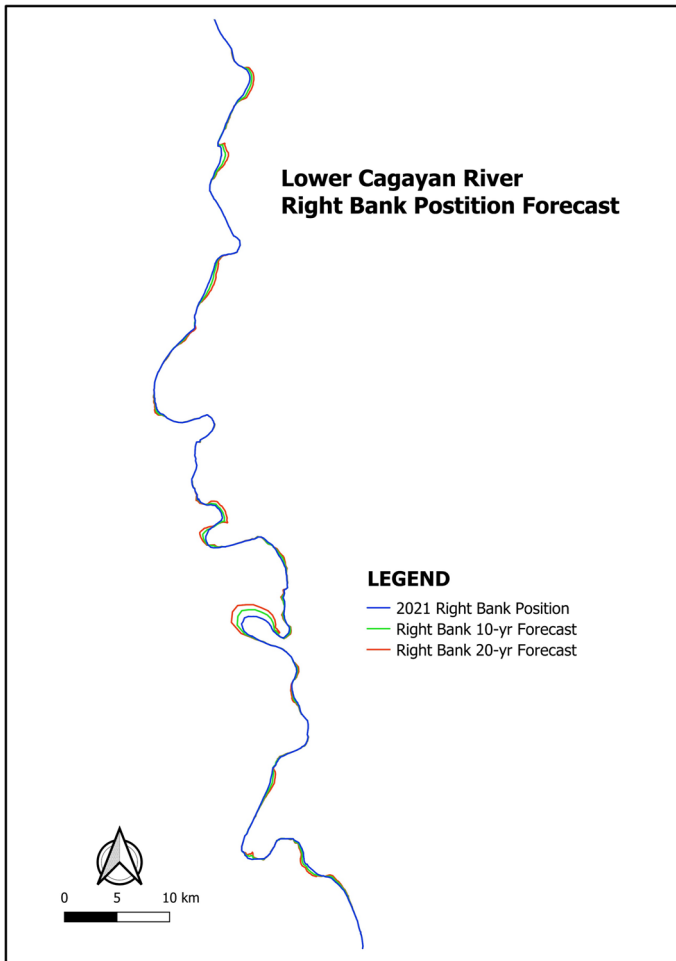


Fig. 13 LCR left bank position forecast

due to the unavailability of a road network. To gather relevant soil data, a reevaluation of the possible replacement sampling sites is conducted by considering the observed process along that river bank provided that it is accessible. The sampling locations (Fig. 14) consist of six (6) erosion and two (2) accretion sites.

All the erosion samples except the river bank soil sample were acquired from Brgy. Ajat, Iguig, and Cagayan have a sand percentage of over 90% and a very low clay content which is less than 4% in all samples. Brgy. Calamagui, Amulung, Cagayan; Brgy. Gammad, Iguig, Cagayan; Brgy. San Lorenzo, Iguig, and Cagayan have a sand portion of 98.82%, 98.12%, and 98.04%, respectively. While Brgy. Magalalag East, Enrile, Cagayan and Brgy. Bagay, Tuguegarao City, Cagayan has sand percentages of 96.6% and 90.81%, respectively. Soil Sample from Brgy. Ajay, Iguig, and Cagayan have a sand percentage of 75.32% which is lower than the other samples, and an estimated silt percentage of 21.8%. On the other hand, the accretion samples at Brgy. Estefania, Amulung, Cagayan and Brgy. Divisoria, Enrile, and Cagayan also have high sand percentages at 99.75 and 97.55% respectively.

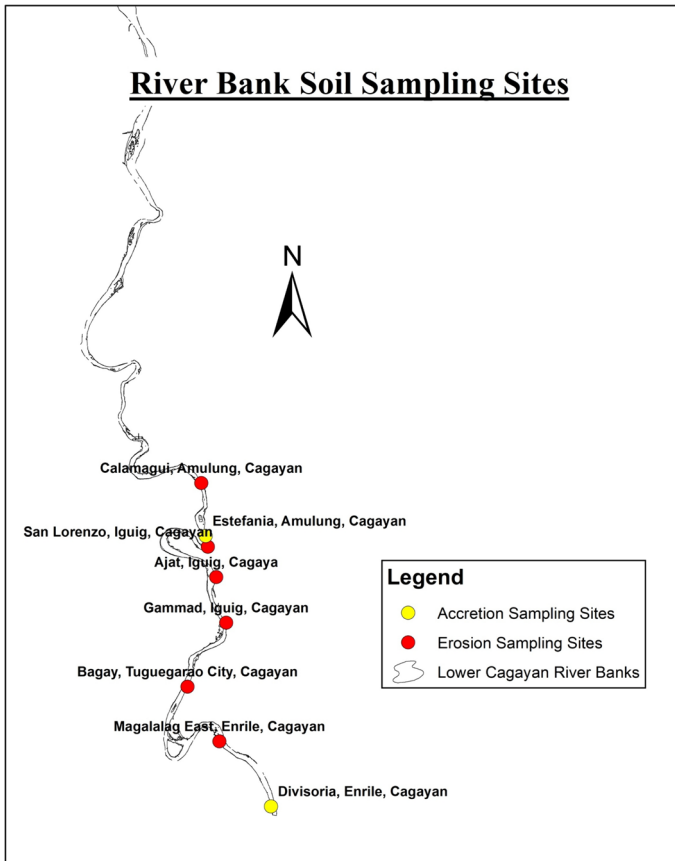


Fig. 14 River bank soil sampling locations

This indicates that the river bank materials are deposited as sediments along the inside bends of the river sand and it can be deduced that silt and clay particles remain longer in suspension which can be considered as pollutants as it impacts the quality of water for fish and other flora and fauna, and even diminish river quality for recreational purposes (Gupta et al., 2023). River banks erode due to high sand concentrations and from previous discussion, the accreted river section forms a new bank that will be dominated by sand particles. River bank soil samples with a high proportion of sand cause significant erosion and eventually, channel widening because they cannot tolerate the stress created by the fast-flowing water (Bhowmik et al., 2018). The accretion process also reduces the carrying capacity of the river section which can cause overtops which is widely observed along LCR communities during high flows. Clay particle proportions in all samples are so minute. Clay is significant in terms of bank stability due to its plasticity and cohesive properties as clay particles stick and cling together as a result of attraction with water. Cohesive soil is defined as having more than 50% silt and clay particles by weight (Mitchell & Soga, 2005). Sand, on the other hand, is considered to be non-cohesive. This indicates that the LCR river banks, due to their soil composition (Table 6) are prone to erosion brought by raging water.

Table 6 Calculated soil type percentage of soil erosion samples

Erosion							
Soil fraction	Brgy. Magalalag East, Enrile, Cagayan (%)	Brgy. Bagay, Tuguegarao City, Cagayan (%)	Brgy. Gammad, Iguig, Cagayan (%)	Brgy. Brgy. Ajat, Iguig, Cagayan (%)	Brgy. San Lorenzo, Iguig, Cagayan (%)	Brgy. Calamagui, Amulung, Cagayan (%)	
Sand	96.60	90.81	98.12	75.32	98.04	98.82	
Silt	2.80	8.01	1.71	21.48	1.32	1.00	
Clay	0.59	1.18	0.22	3.20	0.64	0.18	

3.7 Impact assessment of the impacts of the future changes to infrastructure and agricultural land area

The DSAS-generated future LCR bank line positions were superimposed on the current areal image of the Cagayan River Basin using Google Earth Pro. It is predicted that a number of settlements which includes houses, business buildings, and other infrastructure along the predicted susceptible location, tend to get eroded in the next 10–20 years without proper intervention. This probable scenario will displace thousands of individuals following the trend based on 30-yr river bank line migration data. Also, infrastructures like roads near the river banks are most likely to get eroded. While economical and environmentally sustaining options in arresting river bank erosion are not yet explored in several portions of the river bank, current projects such as river bank concrete lining and rip raps may inhibit the predicted bank failures in identified critical areas. Such channels as of the moment may exhibit static behavior that the forecasted river bank movement will not be realized in the near future.

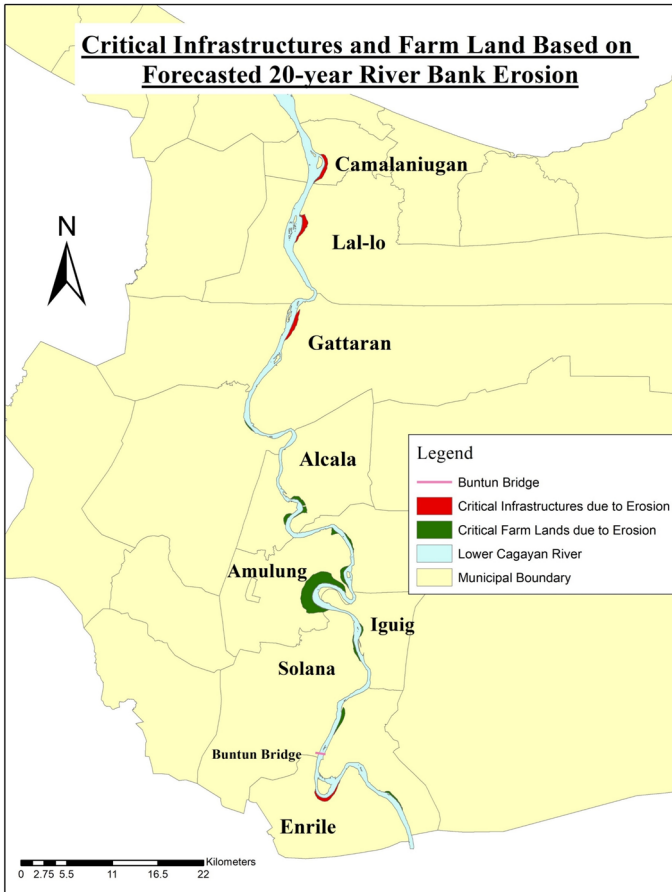


Fig. 15 Location of critical infrastructures based on 20 year river bankline position forecast

The overall assessment predicted erosion and accretion area has highlighted the vulnerable infrastructure mostly, human settlements and farm-to-market roads. Accurate monetary estimates of future damages which this study is unable to develop can use these findings as a basis. The future impacts of erosion and accretion to infrastructures should not be only contained in the destruction of properties but the loss of economic security caused by evacuation and human displacement. Moreover, approximately about 1600 ha of agricultural land is projected to be eroded in the next 20 years (Fig. 15) which will add a toll on the total future damage due to the risk of erosion and its corresponding hazard.

The LCR is laid along the valley floor with direct tributaries diverging water and sediments along the channel. During high flows, as affected by the actual conditions i.e., lack of riparian buffer, prevalent shallow rooted plants, agriculturally modified landscapes, settlements, and extensive soil pavements, etc., the overall hydrologic scheme of the LCR affects floodplain hydraulics. As mentioned in the results section, the overall rate of accretion signifies that alluvium does not only directly source out from eroded river bank soil masses but also to the sediments carried from the upstream of the main Cagayan River, the tributaries, and even laterally discharging overland flow from the flood plains. Upon considering the major outcomes of the study, discussing the importance of floodplain and riparian environments seems to be underrated when talking about human safety and community protection. Nevertheless, the significance of the latter should also be taken into light. Cramer (2012) stated that if the poor status of watershed tributaries is not addressed beforehand or concurrently, stream restoration efforts focused only on the river and its riparian zone will falter or not last. This is because conditions in contributing watersheds are reflected in impaired river systems. Every watershed in the working landscape that is affected by degradation or alteration has comparable patterns, from densely urbanized watersheds to agricultural areas and vegetation wildlands used for grazing and forest exploitation. On a watershed scale, riparian vegetation serves a number of purposes. It gives the watershed surface strength and roughness, which slows the flow of water and increases erosion resistance. Recent studies also focus on river restoration programs that address floodplain soil security and other measures such as bioengineering approaches that promote woody vegetation along river banks not only increase river bank stability but contribute to climate change mitigation (El Hourani & Broll, 2023; Symmank, et al., 2020).

It is also worth noting to consider the effect of the radius of curvature of the meander bends in terms of the river bank migration. Early research on the relationship between curvature and migration rate revealed that migration rate peaks when the radius of curvature is roughly two to three times the width of the river (Hickin & Nanson, 1975; Nanson & Hickin, 1983), but the research conducted by Sylvester et al. (2019) suggests that exceptions with minimal migration appear to be related to the low erosion potential the outer bank rather than the flow characteristics of the river. From their study, they observed that bends with the highest curvatures exhibit the highest migration rates. This may be happening in the meander bends of the LCR (Figs. 11 and 12). The observed bank line migration is found to be more prevalent along the meander curves, future erosion risks have been forecasted (Fig. 15). High river bank migration along the meander bends was found in S2. It is where the highest river bank change in position was observed and is projected to still happen in the future for the most curved meander implying that in accordance with the latter study, the variability of the material erodibility may affect the overall sedimentation and erosion behavior of the LCR bank lines. In combination with the theory that the shear stress and centrifugal force acting on the outer bank increase with curvature, which insinuates that high-curvature bends are highly attributed to large migration rates as a result, but with corresponding lags depending on river setting and location (Donovan et al., 2021;

Sylvester et al., 2019). Nevertheless, for this study, the future impacts were assessed in terms of the susceptibility to erosion due to observed river bank migration as it imposes a high risk of erosion, particularly in critical bend curvatures (Ferdoush et al., 2022). Findings of this study should be considered with careful consideration in mind that prediction of river bank erosion and migration is a tedious and difficult process, and associated variability arises due to continuous river and floodplain modifications, alteration of physical watershed conditions, and climate change (Langhorst & Pavelsky, 2023). The results of the study imply that thousands of infrastructures which include business establishments, houses, and even road networks are susceptible to erosion for the next 20 years, which is quantified to be worth millions of pesos. Approximately, 5982 units of buildings including houses, business establishments, and other infrastructures are being threatened by erosion. Furthermore, since corn is the main commodity of the classified vulnerable areas, it is estimated that in the next 20 years, with a yield of 6000 kg per hectare (Cañete & Alvarez, 2021), the total corn production of the region will decrease by about 35,000 metric tons. These values imply that if the current setting prevails in the future, huge economic consequences may be experienced by the respective riparian communities, not only in monetary accounts but also by difficulties such as human migration and loss of livelihoods.

4 Conclusion

The application of RS and GIS is once again proven to give satisfactory estimates in assessing the spatial and temporal changes of the LCR Bank lines in terms of erosion and accretion. Also, the role of the GEE platform is monumental in the successful promulgation of this data-dependent study. In addition, integration of the Digital Shoreline Analysis System has been crucial in predicting the future river bank positions and assessing the impacts of these changes on the important economic activities and existing condition of the area, the DSAS program was also pivotal in assessing the critical areas with regard to infrastructure and the related economic impact on the nearby community. It has been found out that from 1991 to 2021 erosion is more pronounced than accretion with a 30-year eroded area of -2973.73 ha and an accreted area of 2276.40 ha. The S2 is the most critical section of LCR in terms of past erosion and accretion events attributed to its more notable curvatures. Since 2015 the estimated accreted area is also higher than the observed eroded area which can be a function of river engineering measures over the years or it can be associated with the time lag that it takes for sediments to get deposited. In terms of river bank line dynamics, the LCR left bank is more mobile than the right bank. This was supported by the results of the soil particle size distribution analysis which revealed that the riverbank soil samples taken near the meandering portion of S2 have around 98% of sand content. In accordance with the results of the study, it can be asserted that LCR is an active river. Therefore, natural processes such as erosion and accretion are not unusual, let alone uncommon in nature. It is the way rivers come to life, and by doing so it simply tells us that it is functioning. However, due to human imposed restrictions in terms of the way we have inhabited and modified the floodplain and riverine areas. As presented in this study, the migration of LCR due to the continuous process of erosion and accretion can become a serious threat that can jeopardize lives, livelihoods, properties, infrastructures, etc. This study creates an avenue for future researchers and policymakers to explore the different aspects that influence river bank shifting and channel migration in developing policy recommendations to address the assessed and foreseen adverse impacts of river erosion and accretion. However,

the provision of thorough and multi-parameter assessment is not the main purpose of this study but the systematic observation and quantification of LCR planform dynamics based on historical river bank positions. The lack of fervent field validation and data gathering for possible multi-variable ensemble that can further improve the prediction of LCR movement and a more ardent consideration of the social and environmental factors concerning affected by LCR dynamics is also recognized. Among these is the need for a more dense river bank soil sampling for particle size distribution. Nonetheless, the output of this research simply supplements the ambiguity of visualizing the devastating impacts of river erosion and accretion. Ergo, in order to become beneficial and advantageous, this study highlights the need for a successive and holistic-transdisciplinary approach in addressing and solving issues related to river planform dynamics and morphology.

5 Policy recommendation

This study serves as a comprehensive overview of the variability of the river bank positions of the LCR as affected by the erosion and accretion process. It is imperative to come up with relative and significant recommendations based on the results generated as changes in a river system significantly impact the community and its stakeholders. For this matter, the following recommendation is hereby offered to further improve our interventions in attaining social security, meeting human and environmental interests, and mitigating relative issues that can emerge in the future.

5.1 River bank restoration and rehabilitation

Engineering measures to mitigate erosion and floods in the area include bank stabilization using cement lining, which serves nearby communities by arresting river bank movement. However, these measures are expensive and often cause more harm than good. There is no existing biological and environmental approach to stream bank restoration and rehabilitation in the area, and the buffering and riparian vegetation are not thick and dense enough compared to the extensive agricultural and floodplain cultivation. Current river construction engineering provides instant support and results but overlooks the relative impacts on biodiversity along the river reach. Long-term solutions are still the best, considering other aspects aside from human safety. River stabilization is considered a direct alteration of the river process, and inhibiting the river from moving may result in degradation. This study suggests exploring options that utilize floodplain and riparian greens and other biological measures to restrain erosion. A more in-depth study concerning the future impact of river structures is needed, simulating hydrological scenarios to quantify risks associated with decisions or projects and considering alternative viable options.

5.2 Floodplain and agriculture

Food security is a pressing issue, and the conversion of forest lands to agricultural lands is a significant driver of soil erosion and river sedimentation. Floodplain conditions play a crucial role in minimizing erosion and reducing overbank flows, as vegetation in floodplains minimizes erosion. The LCR's floodplain has been heavily modified for agricultural purposes, highlighting the need for interdisciplinary collaborations to evaluate the impacts

of agricultural practices on the river and watershed. This includes weighing the options of continuous occupancy of the riverbank domain, expenditures on river structures, aquatic life, and biodiversity. Successfully establishing and defining the actual impact of agricultural activities can help solve a significant part of the problem.

5.3 Assessment of LCR tributaries

One of the limitations of this study is to account for the contribution of the tributaries to LCR processes. There is a lack of detailed reports and studies that tackle the impact due to the modification and degradation of river tributaries not only in terms of sediment inflow and flow discharge but on the whole system involving water and river quality for fish, terrestrial and aquatic flora and fauna, and river morphology. It is suggested to conduct a systematic and robust study to estimate the contribution of tributaries to the main river downstream to address issues that disrupt the river systems of such tributaries which also impacts the LCR main river system and its communities.

5.4 Human displacement and livelihood reinforcement

There is always a limit to what humans can do. No matter how much we try to influence the rivers to conform to us, and our society, the problem will not simply stop there. Based on the future bank line positions that were forecasted using 30-year historical data, it is just right to imply the need for strategic planning concerning human displacement and loss of livelihood. The majority of the households along the LCR are farmers. The extent of erosion that was estimated for the next 20 years is more than 700 hectares in terms of human settlement alone, where it also imposes a serious threat on way bigger agricultural areas. Just by these figures alone, the concerned government agencies should be in working harmony to solve such challenges. While it is not within the bounds of this study to technically include human dimensions in terms of livelihood and income generation activities, it is still important, above all, to consider the welfare of the people.

5.5 Assessment of existing erosion, sedimentation, and other mitigation measures

Climate change is exacerbating natural disasters and disrupting environmental processes that induce different consequences. The severity of climate change is evident in the modern world, and existing programs and agendas are not spared. Governments and agencies are working to develop climate-proof strategies, but there are still factors to address, including immediate response in river engineering and hydraulics among which is the provision for a more dense soil sampling along the banks of LCR which is crucial in understanding the LCR dynamics. The worsening climate impacts increase the sensitivity and pressure to withstand interventions. Designing structures should consider the climate outlook, potential hazards, and non-climatic stressors that can affect rehabilitation and restoration measures. Authorities should not stop exploring opportunities to strengthen social, food, and economic security, while also considering the benefits of watershed and river-based measures for stakeholders.

Acknowledgements The author would like to recognize the combined efforts of Engr. Jayzelle S. Ventura, Engr. Czarimah L. Singson, Engr. Christine Gay P. Liberato, Engr. Andy Mulato, Engr. Eisen Hower Abaya, Engr. Englebert O. Manmano, and Mr. Raymark P. Liberato for their valuable insights, help, and encouragement; Prof. Artemio A. Martin, Jr., for hosting the authors/researchers in his Laboratory to perform the soil analysis; and to all colleagues and individuals whose names are not mentioned but positively impacted the authors in carrying out the study.

Author contributions A.J.B.F. conceptualizes the study and has conducted the major literature review, data gathering, and analysis. L.A.A. is a major contributor to the improvement of the objectives and methods of the study. R.J.P and J.L.R.B. helped with the laboratory analysis and other technical aspects of the study. All authors contributed to the writing of the manuscript and the review of the literature.

Funding No funding was obtained for this study.

Data availability The corresponding author will provide the data upon reasonable request, which supports the findings of the study.

Declarations

Conflict of interest The authors declare no competing interests and did not receive financial support from any organization.

Ethical approval and consent to participate Not applicable.

Ethical Responsibilities of Authors The authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of authors" as found in the Instructions for authors.

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