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Spatial Changes in the Fluvial Landscape of the Bone River and Socio-Economic Impacts through Geospatial Technology Integration (Landsat-GIS) in the Gorontalo Region

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Abstract: Changes in river systems can significantly impact communities, particularly through property and infrastructure losses. This study investigates the fluvial landscape changes of the Bone River and their socio-economic implications in the Gorontalo region from a spatial perspective. The research employs multi-temporal Landsat satellite imagery from the Google Earth Engine platform to analyze environmental dynamics in the study area over the period 1995–2025. The imagery dataset includes Landsat 5 TM (May 5), Landsat 7 ETM+ (February 17), Landsat 8 OLI/TRS (October 19), and Landsat 9 (May 31). The results indicate notable changes in the river's course. Evidence of erosion and sediment deposition was identified along the Bone River banks. The patterns reveal a tendency toward lateral migration of the river channel, horizontal shifts, and narrowing of downstream segments. Several natural cut-off points have formed, along with shifts in the main channel in the upstream and midstream segments during the 1995–2025 period. The lateral migration of the river channel reached up to 1.2 km northeastward (N60°E), primarily driven by anthropogenic activities such as traditional sand mining along the western banks and the conversion of riparian land into residential areas. From a socio-economic perspective, these river morphological changes pose potential threats to riverside infrastructure and may trigger land-use conflicts, particularly in areas with active sand mining operations.

Keywords: Geographic Information Systems; Google Earth Engine; Landsat Imagery; River flow; Socio-econom

Introduction

The dynamics of river morphology are a natural phenomenon that occurs independently in alluvial rivers (Kleinhans, 2010). River morphological changes are inherent natural phenomena in fluvial systems, resulting from processes such as sediment transport, water discharge, rock material movement, erosion and accretion (deposition) on floodplains, and channel migration (Gurnell et al., 2016; Palliyaguru et al., 2023; Pu et al., 2022). Global warming influences streamflow magnitude, sediment composition, and variations in hydrological processes, with stronger implications for riverbank erosion and accretion than for alterations in channel course (Duru, 2017; John et al., 2024; Wallwork et al., 2022). Anthropogenic interventions, including the development of hydroelectric dams and irrigation infrastructure along river margins, have significantly accelerated alterations in river geomorphological characteristics (Gupta et al., 2023; Zuo et al., 2020).

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Morphological disturbances in rivers are abrupt phenomena that rapidly alter river courses, often exacerbated by anthropogenic influences. Despite this, they are inherently natural processes that play a vital role in floodplain dynamics. Mechanisms such as channel cut-off and avulsion govern meander evolution and enhance landscape heterogeneity. Channel cut-off occurs when a river adopts a shorter pathway, thereby decreasing overall sinuosity, whereas avulsion entails a complete channel relocation across the floodplain. Avulsion typically arises when sediment deposition elevates the abandoned channel above the surrounding terrain, leading to levee breach and subsequent redirection of flow into a lower-lying course (Camporeale et al., 2005; Weisscher et al., 2019). An analysis of 63 avulsion events in the Andes, Himalaya, and New Guinea basins using Landsat imagery revealed that meandering rivers generate more extreme avulsions compared to braided rivers. (Valenza et al., 2020). The interplay of meander migration, avulsion, and channel cut-off contributes to the formation of complex and heterogeneous floodplains, a finding supported by a global analysis of 10,000 meanders based on satellite imagery (Finotello et al., 2020).

Human settlements exert a significant influence on river dynamics, with floodplains historically serving as preferred habitation zones owing to their accessibility to water resources, transportation routes, and fertile agricultural land (Akhter et al., 2021; Tellman et al., 2021). Interventions such as levee construction for bank stabilization, river channelization, dam development, dredging, and indirect modifications of hydrological regimes, thermal conditions, and sediment dynamics collectively contribute to the reduction of river connectivity (Best & Darby, 2020; Grill et al., 2019; Nilsson & Berggren, 2000). Reduced river connectivity can influence meander formation in sinuous rivers. Several studies have shown that meander formation may actually increase following dam construction due to sediment deficits that enhance riverbank erosion potential (Legleiter, 2015; Shahrood et al., 2020)

Alterations in river landscapes may significantly influence the physical characteristics of river systems, which are strongly associated with patterns of land use in adjacent areas (Koohizadeh Dehkordi et al., 2024; Wohl, E. 2018). Population growth has been inversely associated with the degradation of land cover quality, whereby areas intended to serve as watersheds are increasingly transformed into commercial zones. This transformation has produced significant impacts on the reduction of both the quantity and quality of water resources (Ulfah Utami et al., 2020)

Remote Sensing (RS) and Geographic Information Systems (GIS) provide robust capabilities for analyzing spatial–temporal dynamics through the utilization of synoptic data (Arthun & Zaimes, 2020; Batalla et al., 2018; Walsh et al., 1998; B. Wang & Xu, 2018; S. Wang & Mei, 2016; Zaimes et al., 2019) Furthermore, the analytical strength and integrative capacity of these tools render them more advantageous than conventional geomorphological approaches, which typically demand labor-intensive data collection through field surveys and manual processing. When employed in combination, RS and GIS enable the investigation of river morphological changes that would otherwise remain elusive under traditional methods, primarily due to constraints of time and spatial extent (Walsh et al., 1998).

An additional strength of RS and GIS lies in their reliance on remote sensing datasets that are widely accessible, low-cost, and open-source, thereby facilitating rapid analyses at minimal expense. (Akbar et al., 2019; Dabojani et al., 2014; Puttinaovarat et al., 2021). This technology enables the investigation and analysis of long-term river changes across diverse regions of the world (Shahrood et al., 2020; Sylvester et al., 2019, 2021). Water bodies exhibit higher absorption of electromagnetic energy compared to land surfaces, with the effect being most pronounced in the infrared spectrum (Zhou et al., 2015), Satellite imagery provides the capability to delineate river channels of defined widths and to monitor their morphological transformations across temporal scales. Furthermore, the long-term availability of historical datasets such as Landsat archives dating back to 1984 offers researchers valuable opportunities to investigate meander dynamics and channel migration over extended temporal horizons (Constantine et al., 2014; Valenza et al., 2020).

This study is important because the morphodynamic changes of the Bone River, driven by a combination of natural processes and anthropogenic activities, particularly sand mining and the conversion of riparian land have triggered bank erosion, lateral channel migration, and increased threats to infrastructure and community safety along the riverbanks. The lack of long term spatial-temporal studies in the Gorontalo region necessitates systematic, data based analyses to ensure that watershed management policies are more precise and evidence based. Therefore, this research aims to (1) map and analyze the fluvial landscape changes of the Bone River during the 1995–2025 period, encompassing erosion, deposition, cut-off, avulsion, and lateral migration, by utilizing multi-temporal Landsat imagery through the Google Earth Engine (GEE) platform; and (2) examine the socio-economic implications of these morphological changes for local communities whose livelihoods depend on river based resources.

Method

The methodological framework employs multi-temporal satellite imagery available through the Google Earth Engine platform to investigate environmental dynamics in the study area during the 1995–2025 period. The dataset comprises Landsat 5 TM (May 5), Landsat 7 ETM+ (February 17), Landsat 8 OLI/TRS (October 19), and Landsat 9 (May 31), with temporal benchmarks in 1995, 2005, 2015, and 2025.

However, systematic distortions in Landsat 7 Enhanced Thematic Mapper Plus (ETM+) imagery during 2005–2010 across Indonesia resulted from the permanent failure of the Scan Line Corrector (SLC) on 31 May 2003. This malfunction led to approximately 22% data loss per scene, manifesting as parallel striping (zig-zag) gaps of variable width, which were particularly evident in regions characterized by complex topography (Storey et al., 2014). Indonesia's environmental damage is exacerbated by geographical and climatological factors. As a tropical country with high cloud cover (average >70% according to Supriatna et al., 2018), the combination of SLC-off data gaps and cloud obstruction results in very low image completeness, particularly in Gorontalo Province with its daily cloud dynamics. Therefore, for applications requiring high precision (such as shoreline/river change monitoring), scientific recommendations point to the use of Landsat 8 OLI data (since 2013), which is less affected by cloud interference (Li et al., 2020).

The pre-processing stage includes atmospheric and radiometric corrections to minimize distortions caused by atmospheric factors and to ensure the accuracy of surface reflectance values. Subsequently, the NDVI (Normalized Difference Vegetation Index) analysis is applied to quantify vegetation density and identify land cover changes. The classified NDVI results in raster format are then converted into vector polygon data to facilitate more in-depth spatial analysis. The final stage involves overlaying the NDVI polygon data with river vector data covering the study period, thereby enabling the mapping of river course changes. This methodological approach provides a robust framework for long-term environmental monitoring, particularly in the context of watershed management and the evaluation of climate change impacts.

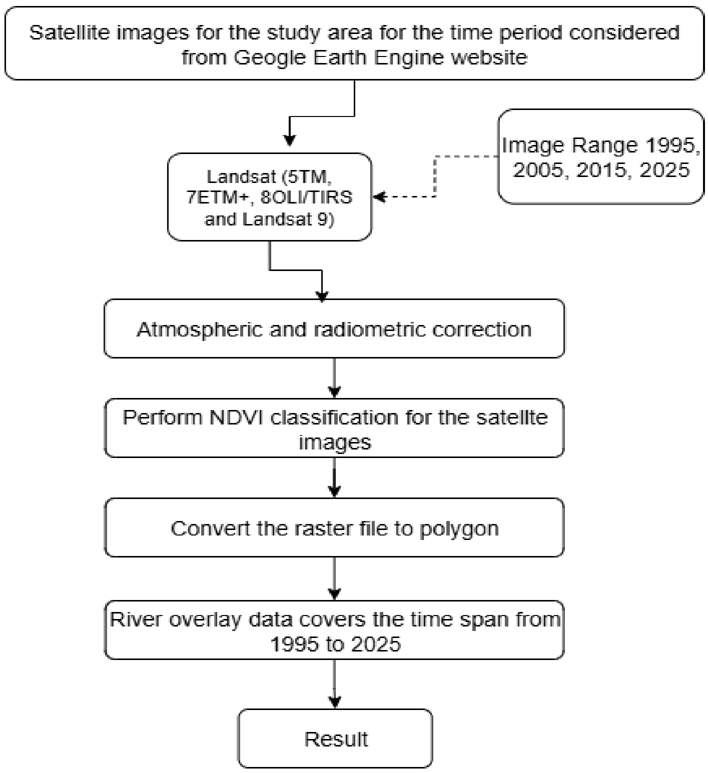

Figure 1. Flowchart of the methodology

Result and Discussion

This study utilizes Landsat satellite imagery as the primary data source to examine changes in river morphodynamics. Landsat data were selected based on technical considerations, as their spatial resolution meets the minimum requirements for analyzing river morphological characteristics, particularly in monitoring fluvial dynamics and channel shifts. The satellite imagery used includes Landsat 5 TM (May 5), Landsat 7 ETM+ (February 17), Landsat 8 OLI/TRS (October 19), and Landsat 9 (May 31), with temporal coverage in the years 1995, 2005, 2015, and 2025, **Figure 2**.

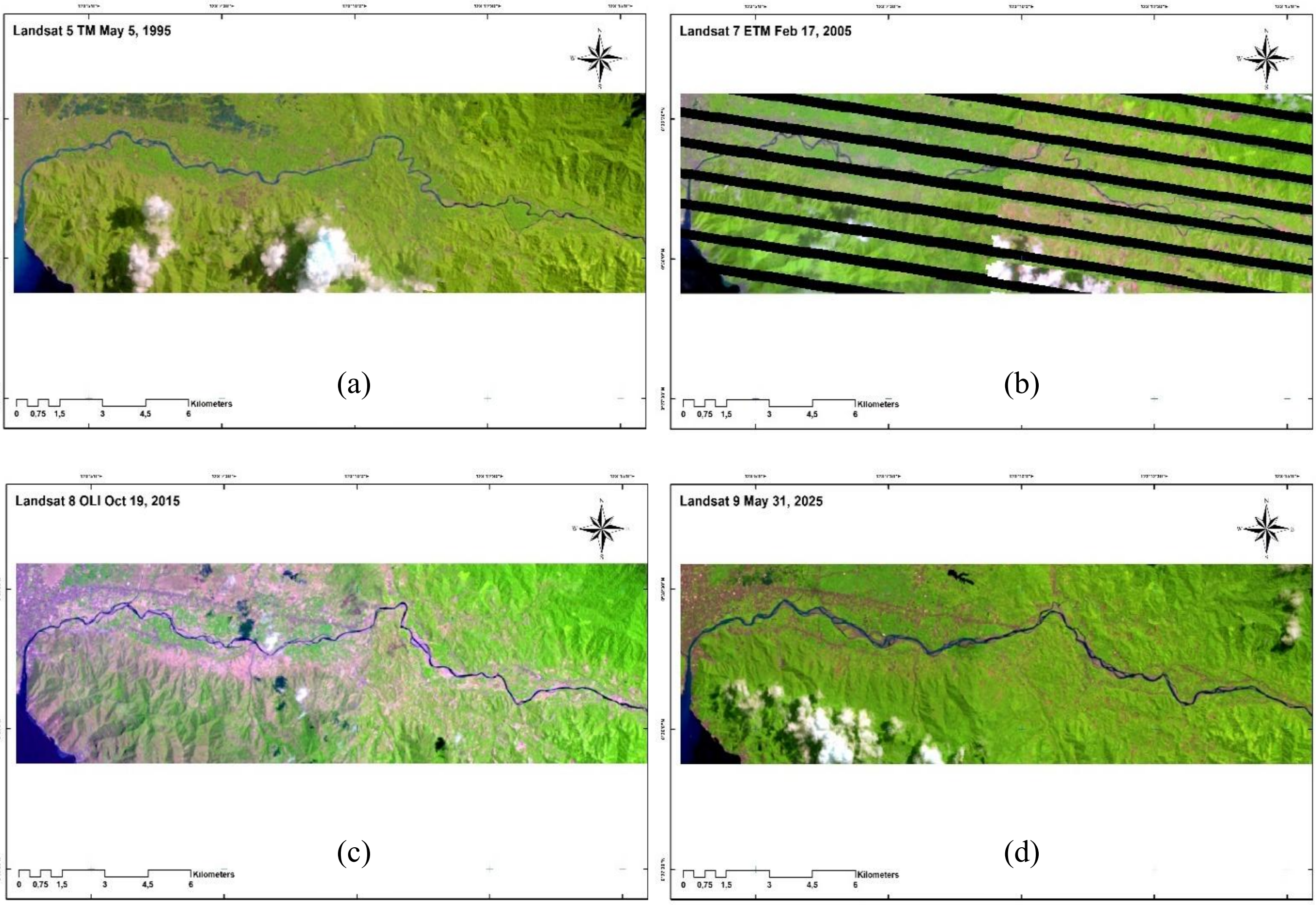

Figure 2. Landsat images of Bone River in 1995 – 2025. Landsat 5 TM May 5 (a), Landsat 7 ETM+ Feb 17 (b), Landsat 8 OLI/TRS Oct 19 (c), and Landsat 9 May 31 (d)

The NDVI (Normalized Difference Vegetation Index) analysis for the period 1995–2025 reveals significant variations in vegetation density across the study area. Based on the classification results, NDVI was divided into five main categories: (1) Non-vegetated land, (2) Very low greenness, (3) Low greenness, (4) Moderate greenness, and (5) High greenness. NDVI values range from 0 to 1, where values closer to 1 indicate healthier and denser vegetation. These variations are influenced by environmental factors such as water availability, soil type, and anthropogenic activities.

Areas with high greenness are concentrated in regions with adequate rainfall and fertile soils, while non-vegetated land is predominantly found in urban areas or regions under high anthropogenic pressure. The analysis indicates that areas with high greenness (NDVI > 0.6) are largely dominated by primary forests or irrigated agricultural land with sufficient water availability. In contrast, areas with low to moderate greenness (NDVI 0.2–0.6) are mainly rainfed agricultural lands. The spatial distribution of NDVI also reflects variations in environmental conditions, where non-vegetated or very low greenness areas (NDVI < 0.2) correspond to settlements, open lands, or regions experiencing degradation due to human activities.

The NDVI data from 1995 to 2025, spanning a 30-year period, serves as a crucial baseline for long-term environmental change studies, including the impacts of climate change, land-use conversion, and anthropogenic pressures on ecosystems. Thus, these results not only provide an overview of past vegetation conditions but also form the foundation for comparative analyses with subsequent NDVI datasets to evaluate spatial and temporal trends in vegetation change. As shown in Figure 2, the 2015 NDVI classification indicates variations in non-vegetation land density (with values approaching 0), which are distributed across residential centers and commercial areas, covering approximately 15–20% of the total study area. This distribution reveals a concentric pattern around urban regions, consistent with the characteristics of urban surfaces (Zhang et al., 2020).

Low greenness (NDVI 0.1–0.2) indicates a high fragmentation pattern in the transitional zones between urban and rural areas, which is strongly associated with less productive agricultural land. This is consistent with the findings of Lambin & Meyfroidt (2021) on land-use transition. Meanwhile, low greenness (NDVI 0.2–0.3) forms corridors along river streams, predominantly occupied by dryland farming systems, in line with the NDVI characteristics of dryland agriculture as described by (Peng et al., 2020). oderate greenness (NDVI 0.3 – 0.6) covers approximately 30–35% of the study area, distributed evenly across transitional zones with secondary vegetation land. Meanwhile, high greenness (NDVI > 0.6) is concentrated in protected areas and primary forests, indicating dense canopy structures and high temporal stability, consistent with the characteristics of tropical forests described by (Asner et al., 2016).

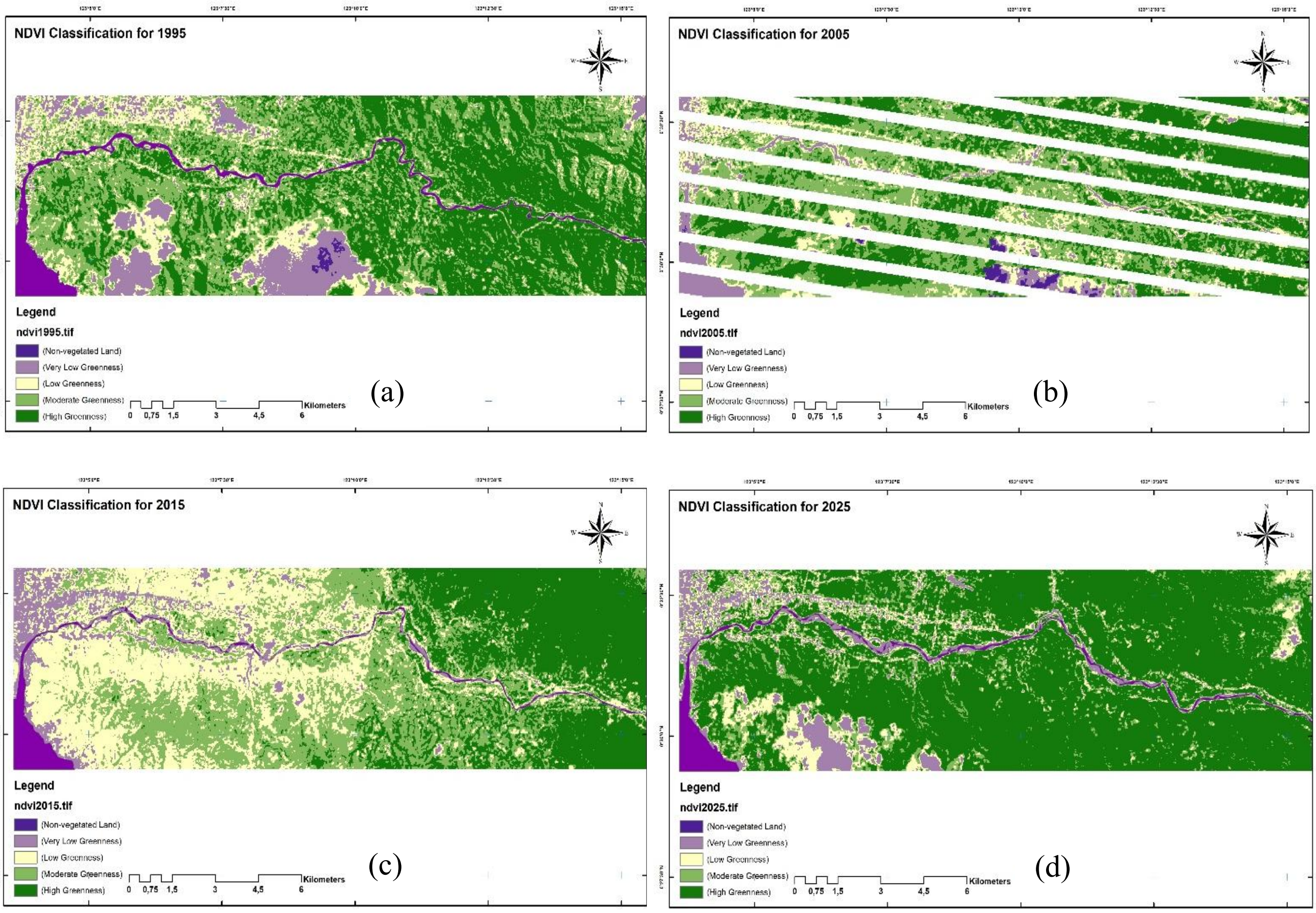

Figure 2. NDVI Classification of Bone River in 1995 (a), 2005 (b), 2015 (c) and 2025 (d)

Vegetation plays a critical role in regulating river flow, reducing flood risk, and preventing bank erosion. Remote sensing data revealed a decline in the Normalized Difference Vegetation Index (NDVI) by 15–20% over the last decade in the upstream region, which shows a positive correlation with the increase in peak discharge during the rainy season (LAPAN, 2022). The reduction in vegetation cover, mainly due to land-use changes such as forest conversion into agricultural land and settlements, has decreased soil infiltration capacity and increased surface runoff, thereby accelerating water flow into the river (Widodo et al., 2023; Deng et al., 2021). This condition can trigger peak flood discharges in impermeable residential areas (Zhang et al., 2022).

The absence of vegetation weakens riverbank stability, increasing vulnerability to lateral erosion, which in turn alters river morphology (Bizzi et al., 2023). Plant roots function as natural soil binders; when vegetation is lost, sedimentation increases and river flow becomes disrupted, thereby accelerating riverbank degradation (Gurnell et al., 2022) (Trigg et al., 2023) It was found that riparian buffer zones can reduce surface runoff velocity by up to 40%, thereby decreasing the risk of flash floods. In addition, vegetation slows down water flow, promotes natural sedimentation, and reduces the river's erosive energy (Wohl et al., 2023).

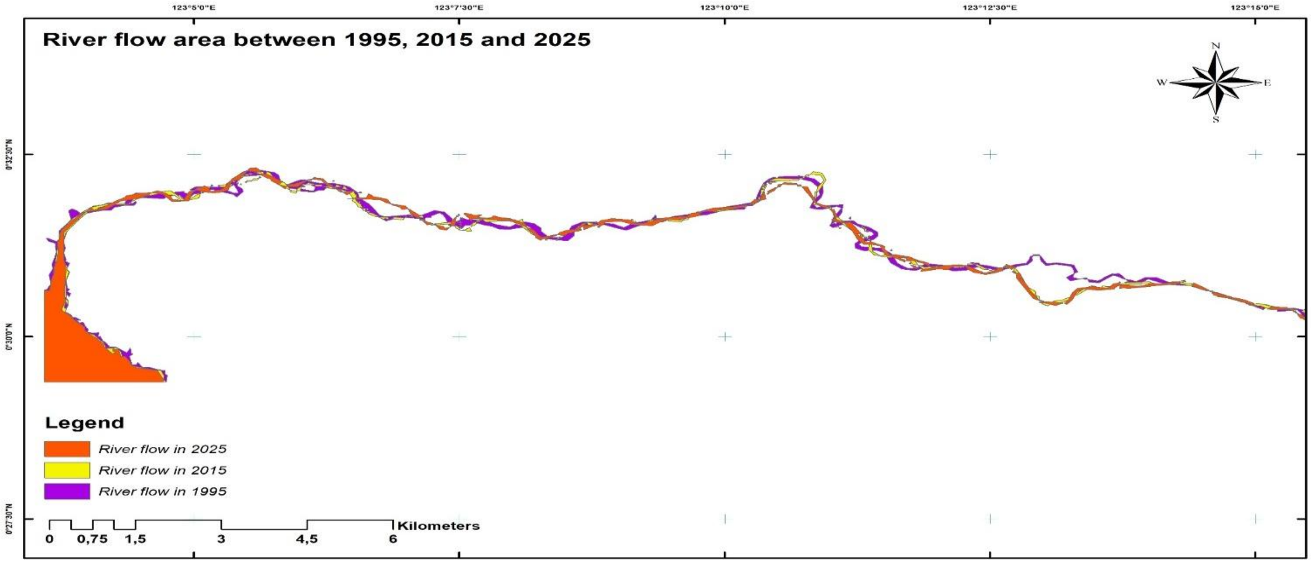

Figure 4. River flow area between year 1995, 2015 and 2025

Based on the spatial analysis shown in Figure 4, river channel mapping using Google Earth Engine produced maps of the Bone River course changes for the years 1995, 2015, and 2025 **(Figure 4)**. Overall, the results reveal noticeable channel shifts along the analyzed sections, particularly in meander areas. These changes indicate ongoing erosion and sediment accretion/deposition processes along the banks of the Bone River.

The observed patterns show a tendency of lateral channel migration in a horizontal direction, with narrowing in downstream segments, which is a typical characteristic of meandering rivers in lowland areas. The migration rate varies along different river segments, with the dominant channel shift oriented toward the northeast (N60°E).

This variation is likely influenced by differences in riverbed material, discharge levels, and anthropogenic activities such as land-use changes along the riparian zone. In addition, several natural cut-off points were identified, formed as a result of intensive meander migration, particularly in areas with high curvature. Temporal analysis further indicates a channel shift in the upstream segment between 1995–2015 and in the middle segment during 2015–2025. These changes suggest high rates and volumes of sedimentation (Awaluddin et al., 2025), which can occur naturally or as a result of human intervention for infrastructure development purposes.

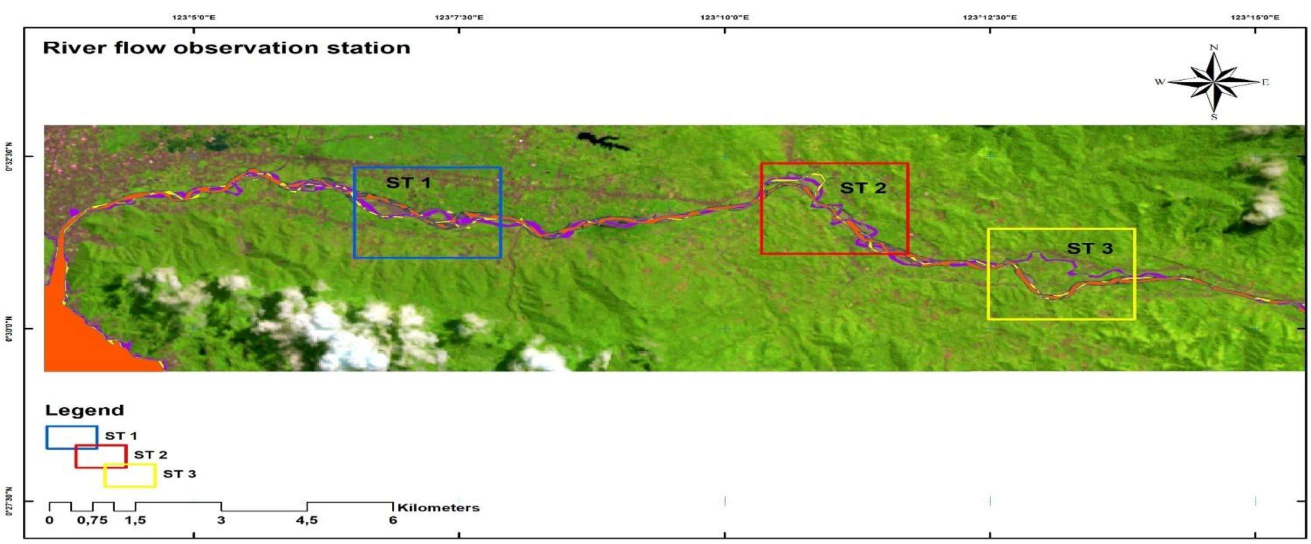

Figure 5. Location of the observation area in initial year 2025

Based on field observations at 18 sand mining sites along the Bone River, various significant impacts on the river's physical condition and surrounding environment were identified. Traditional sand mining has created a reciprocal relationship between the local community's economic demands and the physical changes in the river. The majority of miners 72% are household heads with low levels of education who rely on this activity as their primary source of livelihood. This is particularly evident in Buludawa and Tinelo, where many residents work simultaneously as farmers and sand miners. This phenomenon aligns with Lahiri-Dutt (2018), who highlighted the high dependency of riverine communities on the exploitation of natural resources to meet their basic needs.

Sand mining activities, whether carried out traditionally or using suction machines and heavy excavators, have caused significant changes to the river's morphology. These changes include riverbank erosion, altered flow patterns, sedimentation, and an increased risk of flooding in downstream areas (Bravard et al., 2013; Wishart et al., 2008). The heavy and prolonged rainfall in 2024 caused the Bone River to overflow and the Alale Dam to collapse. As a result, 288 houses across five sub-districts were inundated with water and mud carried by the flood. In addition, a landslide occurred in Tulabolo Village, where six people lost their lives after being buried, 26 were reported missing, and four others were injured (BPBD, Bone Bolango).

Alterations in river morphology, bank erosion, and intensive sand mining activities at several locations, including Pauwo, have resulted in two primary types of erosion: vertical erosion, which scours the riverbed, and lateral erosion, which progressively undermines riverbanks. Koehnken and Rintoul (2018) reported that large-scale sand mining can increase river depth by 3–5 meters through vertical erosion and expand channel width by 20–30% due to lateral erosion. The observed consequences include significant river widening, structural failures such as the collapse of two residential houses, and the destruction of a bridge caused by bank destabilization. Moreover, bank erosion rates were observed to increase by three to five fold in river sections subjected to sand mining activities, highlighting the pronounced geomorphological impact of anthropogenic interventions on fluvial systems (Rinaldi, M., & Simon, A. 2018; Koehnken, L., & Rintoul, M. 2018).

The primary factors driving this process are the mechanical effects of mining activities, which accelerate the removal of riverbed materials, and the loss of riparian vegetation, which normally functions as a natural protective barrier against erosion (Gurnell et al., 2012). Changes in flow patterns and sedimentation due to mining activities at these sites have altered the riverbed profile, leading to the formation of excavation pools. These alterations disrupt the river's flow equilibrium, causing the main channel to deviate toward banks that are more vulnerable to erosion and promoting the development of secondary channels, which can accelerate meander cutoff processes. Furthermore, fine sediments released from the mining sites are transported downstream, resulting in siltation in several river segments. This situation traps local communities in a cycle of environmental poverty, where economic pressures drive excessive exploitation that further exacerbates river degradation and reduces soil fertility(Koehnken et al., 2020). Three approaches are recommended to balance community management rights, environmental stewardship, and sustainable development in the Bone River area: (1) livelihood diversification through entrepreneurship training, (2) the implementation of community-based sustainable mining practices, and (3) the rehabilitation of riparian ecosystems using economically valuable plant species.

Figures 6 and **7** illustrate the significant dynamics of Bone River channel changes over a 30-year period. In segment ST1, lateral channel migration of up to 1.2 km toward the northeast was observed, driven by anthropogenic activities such as intensified traditional sand mining along the western bank and the conversion of riparian land into residential areas. This finding is consistent with previous studies (Hackney et al., 2021) in the Mekong River, where sand mining contributes 50–70% of total lateral erosion. This process is further exacerbated by natural factors, including the unstable characteristics of bank materials and increased erosion intensity during the rainy season (Asgari et al., 2019; Hackney et al., 2020). In segment ST2, the formation of new channels through meander cut-off processes indicates the river's response to anthropogenic pressures concentrated in the meander neck areas (Kondolf, 2006). This phenomenon is further influenced by changes in flow patterns resulting from extreme rainfall variations over the past decade, as documented in regional hydrological data.

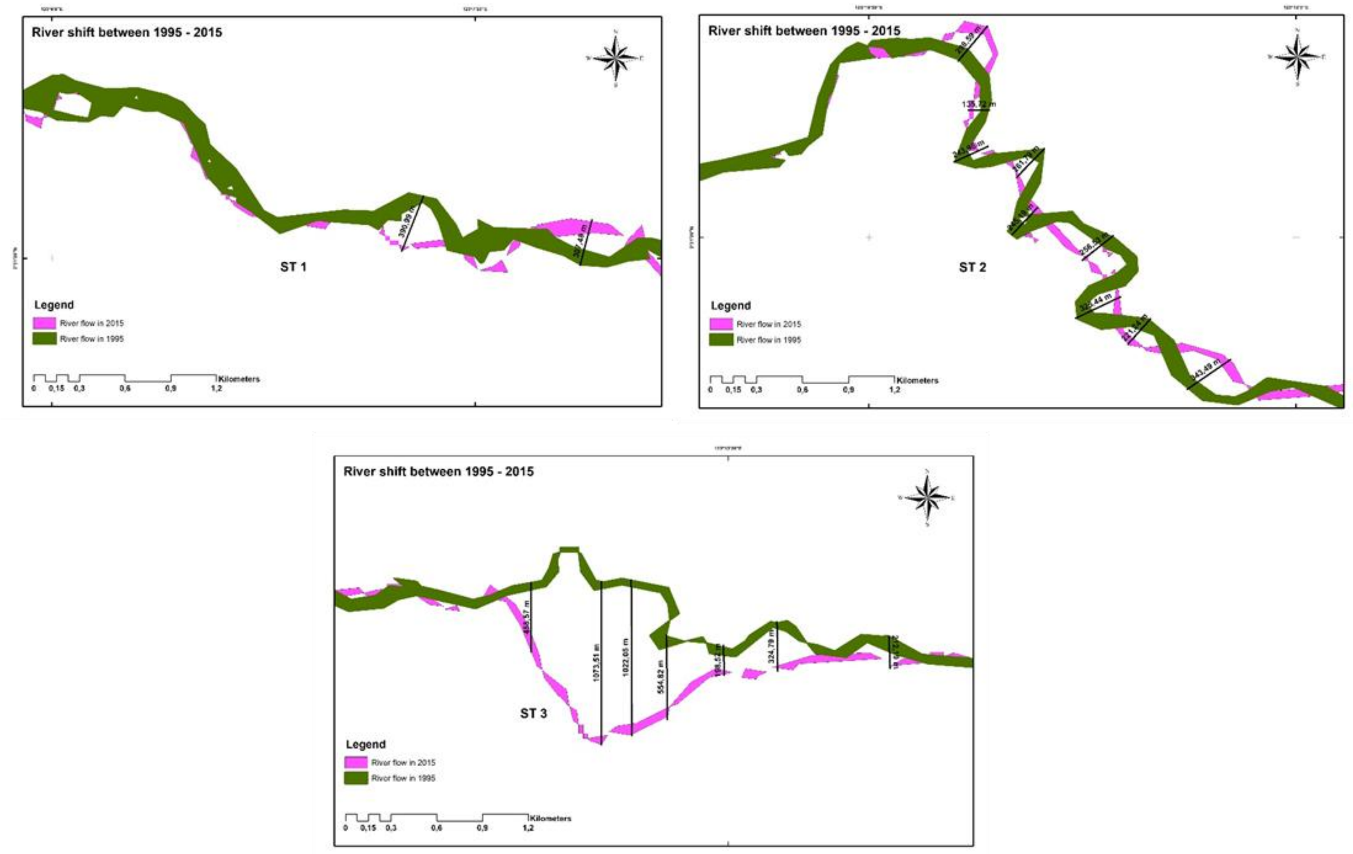

Figure 6. River shift between 1995 – 2015

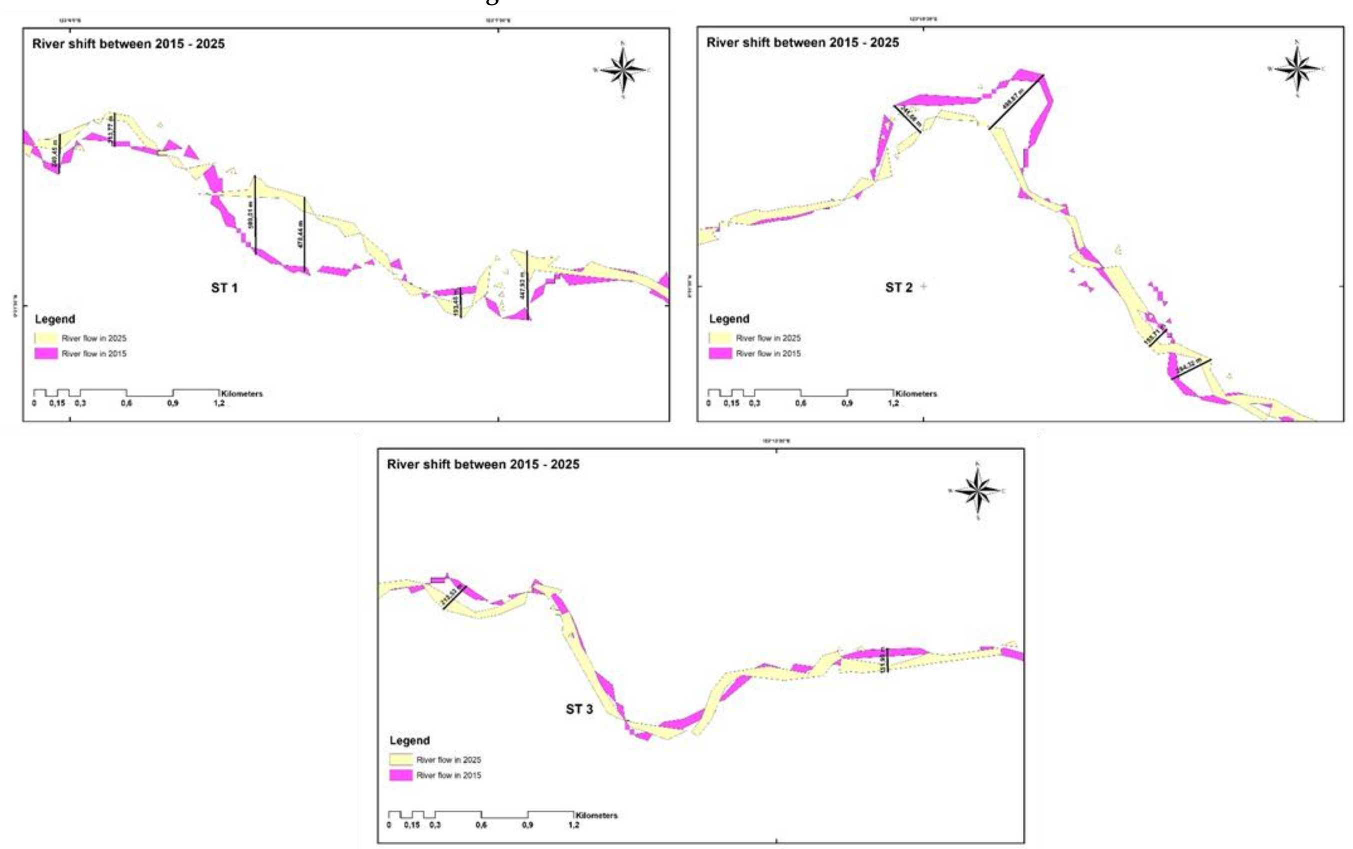

Figure 7. River shift between 2015 - 2025

Meanwhile, segment ST3 experienced the development of multipath channel branching, with an increase in flow area of approximately 0.9 km, primarily due to sedimentation from intensive upstream agricultural activities and flow modifications caused by human-made structures. In ST3, a complete channel shift to a new course on the floodplain, known as avulsion, occurred. This process takes place when sediment fills the old channel to an elevation (aggradation) higher than its surroundings, compounded by mining activities and land-use changes (Chadwick et al., 2020; Gradiyanto et al., 2025; Gearon, J.H., 2025; Zuo et al., 2020)

The resulting environmental impacts include changes to aquatic habitats and riverbank instability, which threaten riparian ecosystems. (Wohl, 2014). From a socio-economic perspective, these changes in river morphology have the potential to threaten riverside infrastructure and trigger land-use conflicts, particularly in areas with active sand mining.

Conclusion

Significant changes in the river channel were observed along the analyzed stretches, particularly in meander areas. Processes of erosion and sediment accretion/deposition were identified along the banks of the Bone River. The observed patterns indicate a tendency for lateral channel migration, accompanied by narrowing of downstream segments. Several natural cut-off points formed as a result of intensive meander migration. Temporal analysis revealed a shift of the main channel in both the upstream and midstream segments during the 1995–2025 period. The primary factors driving these processes are the mechanical effects of sand mining, which accelerate the removal of riverbed materials, and the loss of riparian vegetation, which normally functions as a natural protective barrier against erosion. Lateral channel migration reached up to 1.2 km toward the northeast (N60°E), driven by anthropogenic activities such as intensified traditional sand mining along the western bank and the conversion of riparian land into residential areas. Traditional sand mining has created a reciprocal relationship between the local community's economic demands and the physical changes in the river. The majority of miners 72% are household heads with low levels of education who rely on this activity as their primary source of livelihood.

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Author Contributions

The corresponding author, L.O., proposed the research topic, led data processing and analysis, interpreted the results, and drafted the manuscript. B.J., A.G., and C.D. assisted with data collection, socio-economic analysis, data interpretation, documentation, and manuscript preparation.

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Conflicts of Interest

The authors declare no conflict of interest.

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