Multitemporal Remote Sensing Assessment of Fluvial Dynamics and the Effects of Alluvial mining in the Guaviare River Basin, Colombia

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Abstract

According to official figures, aggregate extraction has intensified along the Guaviare River to meet Colombia's growing infrastructure demands (ANM 2024), raising concerns about its geomorphological stability and the socio-environmental wellbeing of riverine communities. This study combines multitemporal Landsat imagery (1984–2023) with official mining data to evaluate channel migration, erosion, and deposition across a 230 km river reach. Seven meanders were classified according to their distance from principal mining hotspots – high, medium, and low influence – revealing that meanders nearest to extraction sites exhibit up to 60–70 % higher migration rates and nearly double the erosion observed in more distant meanders. A distinct peak in deposition at a medium-influence meander (24.5 km downstream) further underscores the heterogeneity of fluvial responses, which are affected by both direct mining impacts and localized sediment accumulation. Temporal analyses demonstrate a threefold increase in erosion between 2008 and 2013, coinciding with the onset of heightened production (~2012), followed by elevated deposition from 2013 to 2018 and a renewed surge in erosion after 2018. Minimal correlation with deforestation or river discharge levels suggests that aggregate mining is the primary driver of these channel adjustments. However, potential unreported or illicit extraction beyond officially documented sites complicates the assessment, indicating that official records may underestimate the full extent of mining-related impacts. The results highlight an urgent need for integrated management and enforcement strategies that balance economic imperatives with ecological and cultural preservation along the Guaviare River.

Keywords: Alluvial mining, Guaviare river, Remote sensing, Gravel extraction, fluvial dynamics, river water

Introduction

The extraction of sand and gravel, essential materials for global infrastructure development (Padmalal and Maya 2014), has intensified in Colombia due to the growing demand from urbanization, road construction, and civil engineering projects. The Guaviare River, strategically located between the Orinoquía and Amazon regions, plays a critical role as a source of these materials (Minambiente 2023). However, this activity has led to significant socio-environmental challenges, including alterations to river morphology, biodiversity loss, and conflicts with indigenous communities who depend on these ecosystems for their livelihoods(Kondolf 1994, 1997; Kondolf et al. 2002). Despite existing regulatory frameworks, gaps in enforcement and a lack of detailed, multitemporal data hinder effective management of aggregate mining along the Guaviare River. This study leverages remote sensing methodologies, including Landsat (Nagel et al. 2023) imagery from 1984 to 2023, to analyze river dynamics – erosion, sedimentation, and channel migration –

over time. By correlating these changes with extraction intensity and socio-environmental impacts, this research aims to provide evidence to inform sustainable policies and conservation strategies that balance economic development with ecological and cultural preservation.

Methods

The primary dataset consisted of Landsat images acquired from the earliest available date through the present, covering a five-year period. The study area (see Fig. 1) begins at the headwaters of the Guaviare River and extends 230 km downstream, encompassing 170,495.67 hectares distributed across the departments of Meta and Guaviare and the municipalities of San José de Guaviare, Mapiripán, and Puerto Arturo. Within this region, mining hotspots along the river were identified, including key stakeholders, and all relevant features were georeferenced. Special attention was given to estimating extraction volumes, although these figures are incomplete due to the prevalence of informal mining activities that are not reported to government authorities.

Subsequent to data acquisition, a preprocessing stage was carried out to ensure optimal image quality. This included applying cubic resampling to smooth the imagery, adjusting contrast parameters, and using indices such as NWDI (Gao 1996) , MNDWI (Zhou et al. 2015), and various modifications thereof to enhance water feature delineation. The central channel lines and both left and right riverbanks were then manually delineated for every available image within the demarcated area. River migration, erosion and deposition were subsequently determined by overlaying channel riverbanks and centerlines from two different time periods and analyzing channel migration directions.

All riverine areas within the defined study region were then classified. Seven meanders were selected based on their more pronounced and quantifiable meandering behaviors, facilitating measurement and trend analysis; in contrast, other sections exhibited strongly braided morphologies that obscured the identification of clear patterns. Mining-related geographic information was integrated into this analysis to delineate

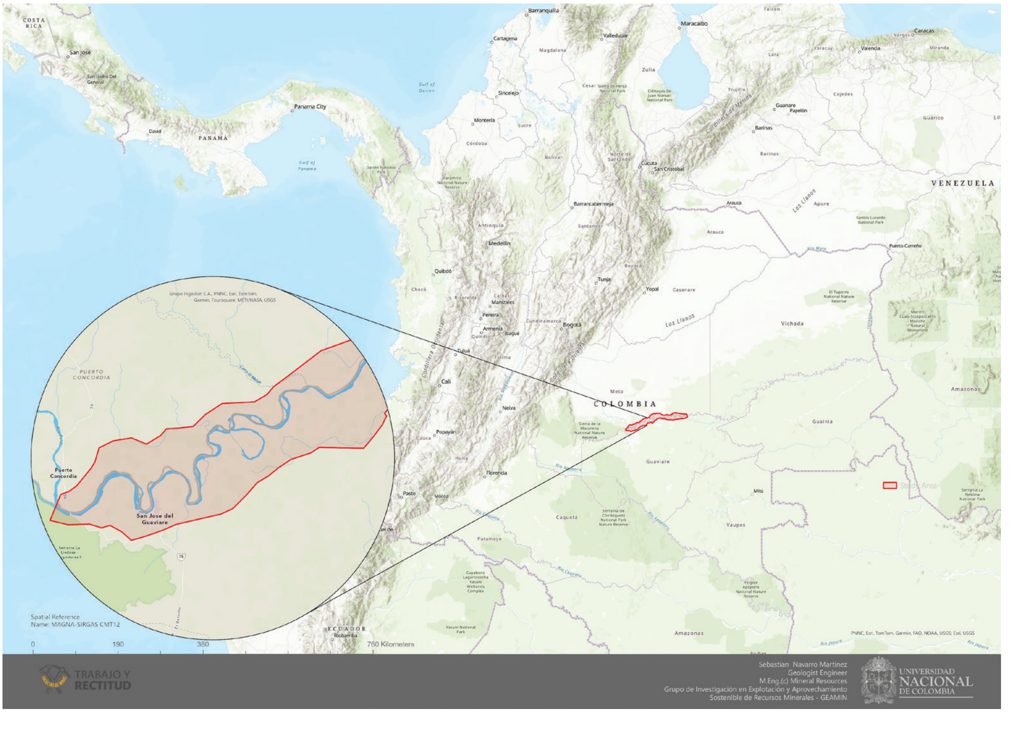

Figure 1 Study Area – a segment of the Guaviare River, Colombia.

areas according to their mining activity. A **direct influence zone** was established for regions where mining titles and active operations intersect the river channel. This zone captures the immediate sections of the channel where extraction activities occur. From this direct zone, a **high-influence zone** was defined by referencing adjacent meanders, resulting in the selection of three proportionally representative meanders near titled areas. Although these meanders are somewhat removed from direct operations, their proximity suggests potential exposure to certain mining-related impacts.

Two **medium-influence zones** were then demarcated. One encompasses the urban center of the municipality of Mariripan; its classification as a medium-influence zone stems from nearby applications for ilegal mining and the likely extraction of construction materials such as sand. The other medium-influence zone, further downstream, includes three additional meanders situated at greater distances from the principal mining activities at San José del Guaviare, where more diffuse impacts may be observed. Finally, two low-influence zones were identified, representing the areas farthest from both mining zones and the meanders in the high- and medium-influence zones. While these more distant areas are less likely to be affected, potential long-term impacts cannot be entirely ruled out, albeit at lower intensities relative to nearer regions.

All available datasets were ultimately integrated, including annual mining production data, total erosion (for each bank), total deposition, and river migration metrics. Hydrological monitoring stations were also considered to investigate possible correlations between fluvial behavior and hydrological trends(IDEAM 2024), thereby providing a more comprehensive analysis of the Guaviare River's response to mining activity and natural geomorphological processes.

Results

The results of this study reveal several notable patterns regarding the spatial distribution of meanders, fluctuations in mining extraction volumes, channel migration rates, and accompanying processes of erosion and deposition. First, the proximity of each meander to the primary mining hotspot allowed for a classification into high-, medium-, and low-influence zones. In Fig. 2, Meanders 1 (4 km downstream) and 2 (8.9 km downstream) were categorized as high-influence due to their relative closeness to intensive extraction areas, whereas Meander 3 (24.5 km downstream) exhibited medium influence, and Meanders 4 (54.8 km) and 5 (63 km), as in Fig. 3, were considered low-influence zones. Although Meanders 6 (152 km) and 7 (205 km) lie substantially farther from the documented mining focal point, reports of illicit or unregulated mining between Meanders 5 and 6 introduce uncertainty, suggesting that these more distant segments may also experience some level of mining-related impacts.

Official data from the National Mining Agency (ANM) on material extraction for the municipality of San José del Guaviare indicate that production volumes of riverine materials followed a rising trend from 2012 through 2019, peaking near the end of this interval, then declining until 2022, and rebounding in 2023. These fluctuations likely reflect shifting economic conditions, regulations, and possibly technological changes influencing both legal and unreported mining activities. Given the potential for unregistered extraction in remote areas, the official records should be interpreted as indicative rather

Table 1 Some of the Landsat images used are shown, with more than 30 in total.

landsat image	Source
LMO5_L1TP_007058_19841209 20200902 _02 T2	https://earthexplorer.usgs.gov/
LTO5_L1TP_006058_19850103_20200918_02 T1	https://earthexplorer.usgs.gov/
LTO4_L25P_006058_19880104_20200917_02 T1	https://earthexplorer.usgs.gov/
LEO7_L1TP_007058_20030104_20200916_02 T1	https://earthexplorer.usgs.gov/
LEO7_L2SP_007058_20080203_20200913_02 T1	https://earthexplorer.usgs.gov/

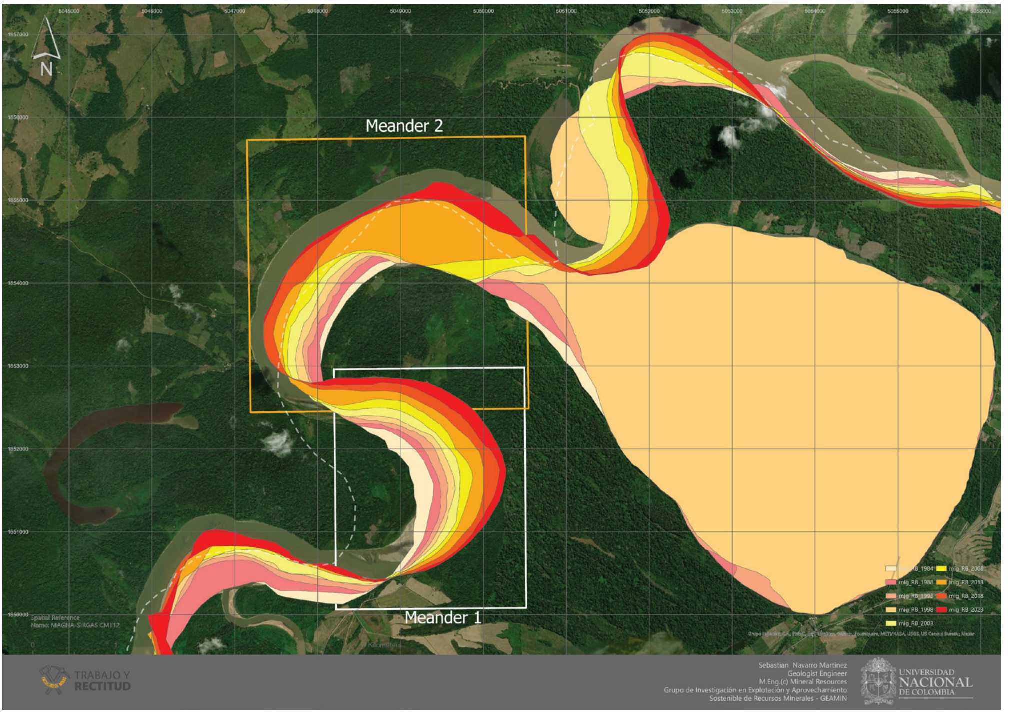

Figure 2 *High mining influence segment: the right bank migration of the river was calculated by analyzing differences between two distinct time periods. Same methodology was applied to assess the migration of the centerline and the left bank.*

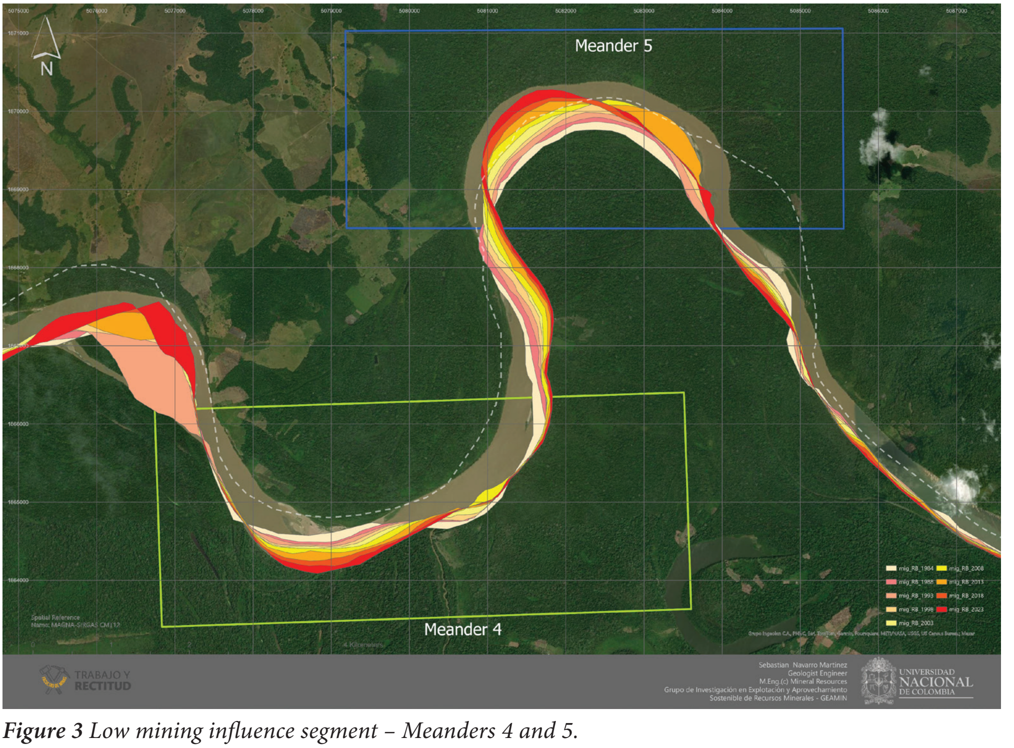

Figure 3 *Low mining influence segment – Meanders 4 and 5.*

than exhaustive. Meanders with high mining influence (1 and 2) show 7% more migration than the meander with medium influence (3) and 64% more than the average of those with low influence (4 and 5). In terms of erosion, the high-influence meanders nearly double the values observed in those with low influence and exceed meander 3 by 25%. In contrast, regarding deposition, meander 3 exhibits such a significant peak (particularly from 2013 to 2018) that it surpasses the average of meanders 1 and 2 by 2% and almost doubles the values of meanders 4 and 5. With respect to migration, between 1984 and 1988 and between 1988 and 1993 it nearly doubles (from about 0.96 to about 1.48 million m²), while from 1988 to 1993 and from 1993 to 1998 it decreases. Until 2003, the values remain around 1.2 to 1.4 million m². Then, between 2003 and 2008 and between 2008 and 2013 there is a jump from about 1.40 to about 1.75 million m². From 2008–2013 to 2013–2018, there is a slight increase (from about 1.75 million m² to about 1.78 million m²), followed by a decrease from 2013–2018 to 2018–2023 (from about 1.78 million m² to about 1.52 million m²). These phases partially coincide with mining extraction between 2012 and 2019, which covers the second half of 2008–2013 and almost all of 2013–2018, during which migration went from about 1.75 to about 1.78 million m² and remained stable. Subsequently, in 2018–2023, migration declined, mirroring the drop in extraction between 2020 and 2022 despite the uptick in 2023. Erosion, meanwhile, gradually increases up to 2003 (1.26 million m², then 1.67 million m², 1.66 million m², and 1.91 million m²) and remains high (about 1.85 million m²) in 2003–2008. However, in 2008–2013 it shows a peak of about 5.22 million m²—almost triple the previous period—then decreases to 2.00 million m² in 2013–2018, and rises again to about 4.20 million m² in 2018–2023. Regarding deposition, it fluctuates around 1.7 to 2.5 million m² up to 2008, stands at moderate levels (about 2.27 million m²) from 2008–2013, and then surges (about 5.10 million m²) in 2013–2018, doubling the previous record. Finally, it drops to about 1.41 million m² in 2018–2023, the lowest value in the entire series.

Additionally, certain observations suggest that unreported mining activity may be influencing fluvial dynamics beyond the officially recognized hotspots (Fig. 4). High values of erosion and pronounced trends of increased erosion and deposition in Meanders 6 and 7, which lie far downstream, could be indicators of undocumented or illegal mining, potentially distorting the geomorphic patterns observed in these reaches. Field observations also showed that when a meander cutoff occurs, downstream scouring can intensify; however, while there was a recent cutoff near Meanders 6 and 7, the trend toward higher erosion and deposition appears to have been established beforehand. A similar cutoff event took place near Meander 3 in the medium-influence zone, briefly altering local fluvial dynamics. In that case, channel processes stabilized after a short period, illustrating the variability and resilience of the river's response to both natural adjustments and anthropogenic impacts.

Deforestation processes were also analyzed using the same images to determine whether the observed changes in fluvial dynamics were linked to deforestation or were intrinsic river processes. No significant deforestation was identified in the selected meanders during the periods of heightened erosion. Additionally, river levels and discharge, obtained from IDEAM stations (Institute of Hydrology, Meteorology, and Environmental Studies of Colombia), were examined; however, no correlation was found between river levels and the intensification of fluvial dynamics.

Conclusions

This research highlights the multifaceted influences of aggregate mining on the Guaviare River. Proximity to the principal extraction hotspot correlates strongly with greater channel migration and erosion, with Meanders 1 and 2 showing migration rates approximately 7 % higher than those of Meander 3 and 64 % higher than low-influence meanders. Erosion near these high-influence meanders is nearly double that of low-influence meanders and roughly 25 % greater than at Meander 3. In contrast,

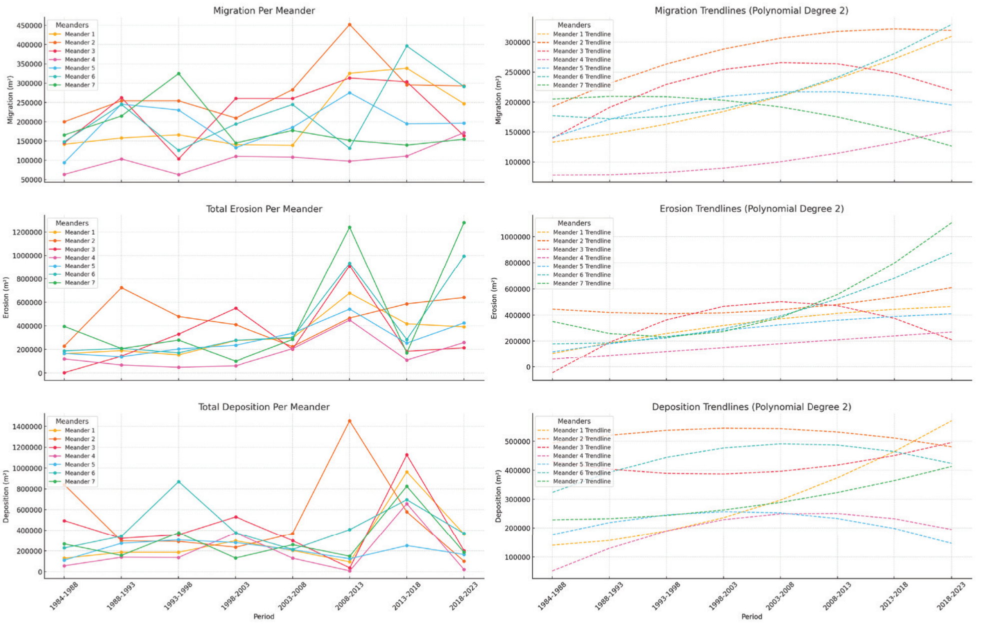

Figure 4 *Graphs of Fluvial Dynamics Analysis.*

Meander 3 exhibits intense deposition – particularly during 2013–2018 – that exceeds by about 2 % the average of Meanders 1 and 2 and nearly doubles the values for Meanders 4 and 5, suggesting localized sediment accumulation driven by both natural processes and mining pressures.

The temporal patterns echo the official ANM data: between 2012 and 2019, extraction volumes increased substantially, coinciding with marked shifts in channel morphology. From 2008 to 2013, erosion rates tripled relative to previous averages; from 2013 to 2018, deposition peaked, while erosion temporarily decreased; and after 2018, erosion again intensified as extraction levels rebounded. These fluctuations underscore the non-linear nature of fluvial response to mining activities. Further downstream, high erosion and deposition values in Meanders 6 and 7 hint at unregulated mining, suggesting that official records may underestimate the actual magnitude and spatial extent of extraction impacts.

Additional analyses reveal minimal deforestation within the examined meanders during the periods of heightened erosion, indicating that the observed fluvial changes are not primarily linked to land-cover alterations. Likewise, correlations with river discharge or levels from IDEAM stations were negligible, implying that mining-driven channel adjustments surpass the influence of short-term hydrological variations. Overall, these findings underscore the necessity for integrated management approaches – encompassing remote sensing, field verification, and robust regulatory oversight – to maintain the ecological integrity of the Guaviare River while acknowledging its central role in economic development.

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