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Research Article

Remote sensing applied to the morphodynamics of the meandering Usumacinta River in the period 1986-2019

Sensoriamento remote aplicado à morfodinâmica do meandrante rio Usumacinta no período de 1986-2019

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Abstract: The Usumacinta River (UR), one of the longest and most voluminous rivers in Central America, is a free-flowing river without significant anthropogenic control. However, its fluvial dynamics and interactions with the environment drive changes that are influenced by the hydraulic, morphological, and sedimentary conditions that evolve. Remote Sensing (RS) and Geographic Information Systems (GIS) are increasingly being utilized for the analysis of historical morphological changes in rivers, offering accelerated and predictive insights. In this study, we employed RS and GIS techniques to examine the morphodynamics of UR from 1986 to 2019, focusing on variables such as channel migration, channel width, sinuosity, and slope. Our analysis revealed that 91% of the 1,458 transects (each 1,400 m) exhibited low migration (<50 m) and only 0.61% experienced high migration (>200 m). The UR is characterized by high sinuosity (S = 2.01) and meandering channels with slopes ranging from 0º to 84º. These findings provide crucial data for policymakers and resource managers, offering a foundation for strategies aimed at protecting, conserving, and sustainably managing water resources in the UR basin.

Keywords: fluvial morphodynamics; channel migration; Usumacinta basin; sinuosity; sediments.

Resumo: O Rio Usumacinta (UR), um dos rios mais longos e volumosos da América Central, permanece como um rio de fluxo livre, sem controle antropogênico significativo. No entanto, suas dinâmicas fluviais e interações com o ambiente impulsionam mudanças influenciadas por condições hidráulicas, morfológicas e sedimentares que evoluem ao longo do tempo. O Sensoriamento Remoto (SR) e os Sistemas de Informações Geográficas (SIG) são cada vez mais utilizados para a análise de mudanças morfológicas históricas em rios, oferecendo insights acelerados e preditivos. Neste estudo, empregamos técnicas de SR e SIG para examinar a morfodinâmica do UR no período de 1986 a 2019, com foco em variáveis como migração do canal, largura do canal, sinuosidade e declividade. Nossa análise revelou que 91% dos 1.458 transectos (cada um com 1.400 m) apresentaram baixa migração (<50 m), enquanto apenas 0,61% experimentaram alta migração (>200 m). O UR é caracterizado por uma alta sinuosidade (S = 2,01) e canais meândricos com declividades variando de 0º a 84º. Esses resultados fornecem dados cruciais para formuladores de políticas e gestores de recursos, oferecendo uma base para estratégias voltadas à proteção, conservação e gestão sustentável dos recursos hídricos na bacia do UR.

Palavras-chave: morfodinâmica fluvial; migração de canal; bacia de Usumacinta; sinuosidade; sedimentos.

1. Introduction

River morphology is shaped by the dynamic interplay between water flow and sedimentary materials within the channel, leading to complex processes of sediment transport, erosion, and deposition (CHURCH, 2006; GURNELL; BERTOLDI; CORENBLIT, 2012; BASILE, 2018). The equilibrium between hydraulic and sedimentary conditions ensures that no two rivers exhibit identical dynamics, even within the same hydrographic region (SCHUMM, 1973; WOHL, 2013; PETRICH, 2018). Among the most studied aspects of fluvial dynamics are channel patterns and the factors that drive their formation. A historical approach is essential for analyzing these factors, enabling the measurement of channel migration rates and assessing their behavior over time (DONOVAN; BELMON, 2019; REYNOLDS; ROYAL, 2020).

Channel migration is a key geomorphological process involving the lateral movement of flow channels, which shape floodplains (LEOPOLD; WOLMAN, 1960; OLLERO-OJEDA et al., 2006). The study of meander cutoffs, which occur when a river creates a shortcut across a meander bend, is essential for understanding these dynamics. Cutoffs impose immediate control on geomorphological evolution by reducing sinuosity and influencing meander migration rates over extended periods (GAO et al., 2024). The processes of cross-circulatory flow and convective redistribution of longitudinal flow velocity significantly influence the morphodynamics of meandering rivers, thereby affecting sediment transport and channel evolution (CHENG; LI, 2024). Understanding these dynamics is critical for managing and mitigating the impacts of anthropogenic pressures and extreme climate events on river systems.

Meander cutoffs, which include neck and chute cutoffs, are fluvial phenomena that have played a crucial role in the evolution of meandering rivers. A neck cutoff occurs when the two limbs of a highly sinuous bend touch, whereas a chute cutoff refers to the formation of a shortcut channel that bypasses a meander bend (GAO; LI, 2024). These cutoffs geometrically constrain the complexity of meander planforms and dynamically interrupt river evolution by generating sediment pulses that affect river migration and dynamics, both locally and at the reach scale (CAMPOREALE et al., 2008; FRASCATI; LANZONI, 2010). Additionally, meander cutoffs leave behind oxbow lakes that serve as valuable ecological habitats (AMOROS, 2001; STELLA et al., 2011) and can influence floodplain sedimentology, contributing to sediment connectivity between the floodplain and the river (AALTO et al., 2008).

The use of remote sensing (RS) and geographic information systems (GIS) to analyze historical and predictive morphological changes in rivers is becoming increasingly prevalent owing to the availability of free satellite image collections and technological advancements (CLERICI; PEREGO, 2016; BOSE; NAVERA, 2017; BATALLA et al., 2018; WANG; XU, 2018; LANGAT; KUMAR; KOECH, 2019; BASNAYAKA et al., 2022). These tools facilitate faster result acquisition and enable continuous, predictive monitoring of river channels, thereby enhancing the understanding of geomorphological forms and processes in rivers (ENTWISTLE et al., 2018; BASNAYAKA et al., 2022). Additionally, studies on meander cutoffs, such as those by Gao et al. (2024), provide critical insights into the hydrodynamic processes that can be analyzed using these technologies.

Kuenzer et al. (2019) explored the potential of Earth observation data for analyzing large river deltas globally, highlighting various RS-derived products for studying river morphology. Entwistle et al. (2018) reviewed the growing use of RS in fluvial geomorphological research, emphasizing data accuracy. Piégay et al. (2020) used RS to review studies on river corridors' past, present, and future conditions, identifying new challenges in river and coastal studies. Langhorst and Pavelski (2023) developed the first global bank erosion dataset by using Landsat imagery. By contrast, Shahrood et al. (2020) and Basnayaka et al. (2022) linked river morphology to time-based changes using Landsat data.

The Usumacinta River (UR) is a significant waterway in Mexico and Central America (SORIA-BARRETO et al., 2018; JUPIN et al., 2024; MEDRANO-PÉREZ et al., 2024), and existing research highlights its importance but reveals gaps in our understanding of its morphodynamics (CASTILLO-CRUZ; MEDRANO-PÉREZ, 2023; MEDRANO-PÉREZ et al., 2024). According to Kemp et al. (2016), the UR is a major freshwater contributor to the Gulf of Mexico and plays a crucial role in regional wetlands. However, the UR may face a significant reduction in discharge (up to 80 %) due to climate change, in contrast to expected increases of 11-63% in other major rivers, such as Mississippi (KEMP et al., 2016).

Several studies have explored different aspects of the UR and its neighboring river systems. Muñoz-Salinas and Castillo (2015) examined the influence of the El Niño-Southern Oscillation (ENSO) on the Usumacinta and Grijalva Rivers (UGR). In the same region, Mendoza et al. (2019) studied the evolution of bifurcation in the Lower Grijalva Basin under anthropogenic flood control interventions, whereas Muñoz-Salinas et al. (2023) proposed new models for the geomorphological evolution of the Lower UGR Basin. Mendoza et al. (2022) analyzed the impact of upstream dams on river bifurcation in the lower Grijalva River Basin, Mexico. Gallardo-Zavaleta et al. (2023) recommended a framework for studying the socio-ecological aspects related to sand and gravel mining at La Isla in the UR Basin. According to Muñoz-Salinas et al. (2017), the coastal plains of Tabasco and Campeche offer direct evidence of UGR evolution, positioning them as one of North America's largest river systems (MUÑOZ-SALINAS; CASTILLO, 2015). Understanding the UR's morphodynamics is thus crucial for better basin and territorial management (VERA-RODRÍGUEZ; ALBARRACÍN-CALDERÓN, 2019).

Despite these advancements, challenges remain in integrating data from different sources and in applying these methods to rivers with unique characteristics, such as those in Mexico. Variability in data quality and resolution, along with methodological differences, can limit the comparability and strength of study conclusions. However, in the case of the Usumacinta River, there is no information on the dynamics of the fluvial morphology of this important river. Addressing these limitations is essential for improving the accuracy and applicability of fluvial morphology research.

This study aims to contribute to the understanding of the behavior of the Usumacinta River by conducting a morphodynamic characterization over the past 33 years using remote sensing techniques. By combining the analysis of historical satellite imagery with field observations, this study aims to quantify morphological changes, map fluvial units, and provide a comprehensive assessment of morphodynamic changes as an initial exploration of this topic in the UR basin. Specifically, this study sought to answer the following key questions: 1. How can remote sensing and GIS tools improve the accuracy and efficiency of monitoring and predicting future morphological changes in the Usumacinta River? 2. What have been the spatial and temporal patterns of channel migration in the Usumacinta River over the last 33 years? 3. Which environmental and anthropogenic factors influence variations in channel width, sinuosity, and slope of the Usumacinta River?

2. Study Area

The Usumacinta River (UR) is considered the largest fluvial system in Mexico and the Mesoamerican region, with a length of 1,100 km and an annual water flow of 1,958 m^3/s (CONAGUA, 2023a; MUÑOZ-SALINAS; CASTILLO, 2015). It originates in the mountains of Guatemala and flows through the states of Chiapas and Tabasco on its way to the Gulf of Mexico (Figure 1A-B; JUPIN et al., 2024). The UR basin covers an area of 7.7 million ha, of which 43.6% is in Mexico and the rest are in Guatemala (56.36%) and Belize (0.04%). The UR Basin is a Mesoamerican biodiversity hotspot (MYERS et al., 2000) and comprises diverse topographic landscapes, from mountainous areas in the Chiapas Highlands to alluvial plains at its mouth in the Gulf of Mexico (Figure 1C-D; JUPIN et al., 2024; CASTILLO-CRUZ; MEDRANO-PÉREZ, 2023; SAAVEDRA-GUERRERO; LÓPEZ-LÓPEZ; CASTELLANOS FAJARDO, 2019). It forms deltaic-shaped mouths, whose movement creates new slopes through lagoons and streams where plant communities that form part of the most important wetlands in the region develop (CONTRERAS-SILVA; TAPIA-SILVA, 2014; OCHOA-GAONA et al., 2018).

In terms of geology, it is composed of Mesozoic and Cenozoic sedimentary rocks of sandstone-lutite, limestone, limestone-dolomite, limestone-lutite, and lagoon (SAAVEDRA-GUERRERO; LÓPEZ-LÓPEZ; CASTELLANOS FAJARDO, 2019). These soils are predominantly cambisols, luisols, fluvisols, gleysols, and rendzinas (CASTILLO-CRUZ; MEDRANO-PÉREZ, 2023; SAAVEDRA-GUERRERO; LÓPEZ-LÓPEZ; CASTELLANOS FAJARDO, 2019). The climate can be considered tropical, where mean temperatures vary little throughout the year (26.8 °C) and mean annual precipitation is high (>2,300 mm), as shown by the Boca del Cerro climatological station (code: 27004) data during the period 1949-2019 (Figure 2a; CONAGUA, 2023b), which directly influences the morphodynamics of the river. According to different characteristics, the basin is divided into three portions: upper basin, middle basin, and lower basin (SAAVEDRA-GUERRERO; LÓPEZ-LÓPEZ; CASTELLANOS FAJARDO, 2019).

The Grijalva-Usumacinta River system consists of the Grijalva and Usumacinta Rivers, which originate in distinct mountainous areas of Guatemala (Figure 1A). Upon entering Mexico, the Grijalva River moves into the mountainous region of Chiapas, whereas the Usumacinta River runs alongside this region. Before entering the Gulf of Mexico, the two rivers converged at a point known as "Tres Brazos" (Figure 1C: 3). The Usumacinta-Grijalva River (UGR) system is a major source of sediment in the southeastern Gulf of Mexico and is crucial for maintaining a dynamic coastal sediment supply. As reported by Soto-Mardones et al. (2023), the sediment generated in the upper catchments of the UGR is transported through the delta plain to the coastal zone. This system ranks second in freshwater discharge to the Gulf, immediately after the Mississippi-Atchafalaya River system, and plays a significant role in regional coastal wetlands and sediment dynamics (KEMP et al., 2016; NOOREN et al., 2017). Figure 2b shows the behavior of the annual water flow (1,958 m^3/s) and annual volume of sediment (7,529 thousand m^3) at the hydrometric station of Boca del Cerro (code: 30019) with the available data in the CONAGUA (2023a): 1948–2022/1951–1980 data range (water flow/sediment, respectively). Additionally, for a better analysis, linear regression was applied to the annual sediment volume from 1950 to 2022 of 6,096.6 thousand m^3. The Pearson's correlation coefficient between mean annual flow and annual sediment volume was approximately $r = 0.49$, indicating a moderate positive correlation and suggesting that as flow increases, sediment volume also tends to increase. However, additional factors, such as topography, geology, vegetation, and climatic conditions, must be included to accurately estimate the sediment transport.

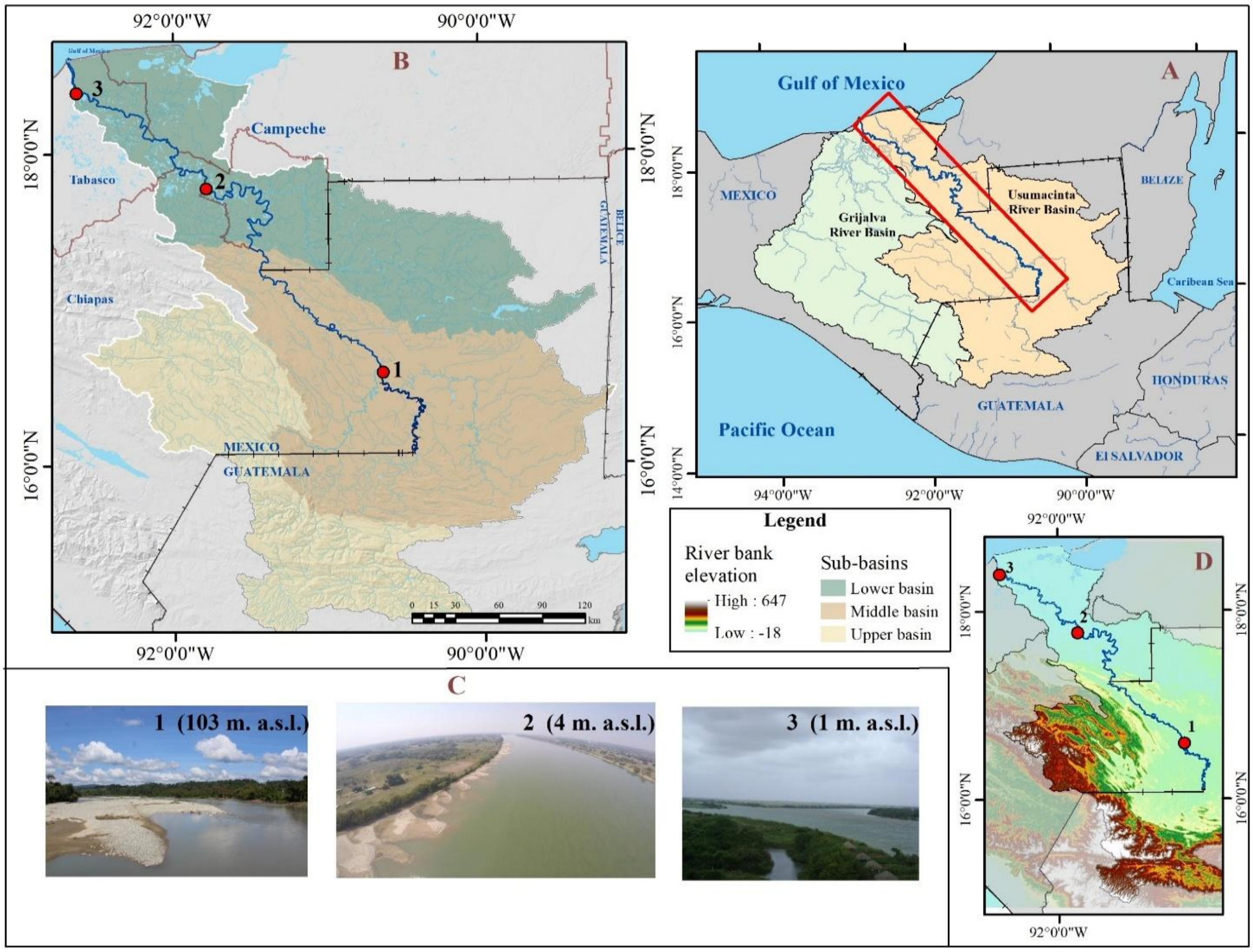

Figure 1. Study area: a) localization; b) UR panoramic (1: Lacantun, 2: Emiliano Zapata, 3: Tres Brazos); c) elevation; d) topographic profile of the UR. Photography by Edith Kauffer.

UR presents a higher specific yield and sediment transport capacity than the Grijalva River with different important seasons in magnitude (MUÑOZ-SALINAS; CASTILLO, 2015) and it is considered a key factor in the formation of the coast of the Tabasco state (MUÑOZ-SALINAS et al., 2017). Unlike UR (GRILL et al., 2019), the Grijalva River is controlled by a system of dams, which may influence the seasonal behavior of sediment. However, the situation of the UR tributaries in the Guatemalan territory is different. Nooren et al. (2017) reported that the Chixoy River hydroelectric dam at Pueblo Viejo, Guatemala, reduced the sediment transport of UR to the coast since its completion in 1983.

In this study, we analyzed only the 700 km that the river runs in Mexico, starting at the convergence point between the Lacantún, La Pasión, and Chixoy Rivers (SOARES; GARCÍA GARCÍA, 2017).

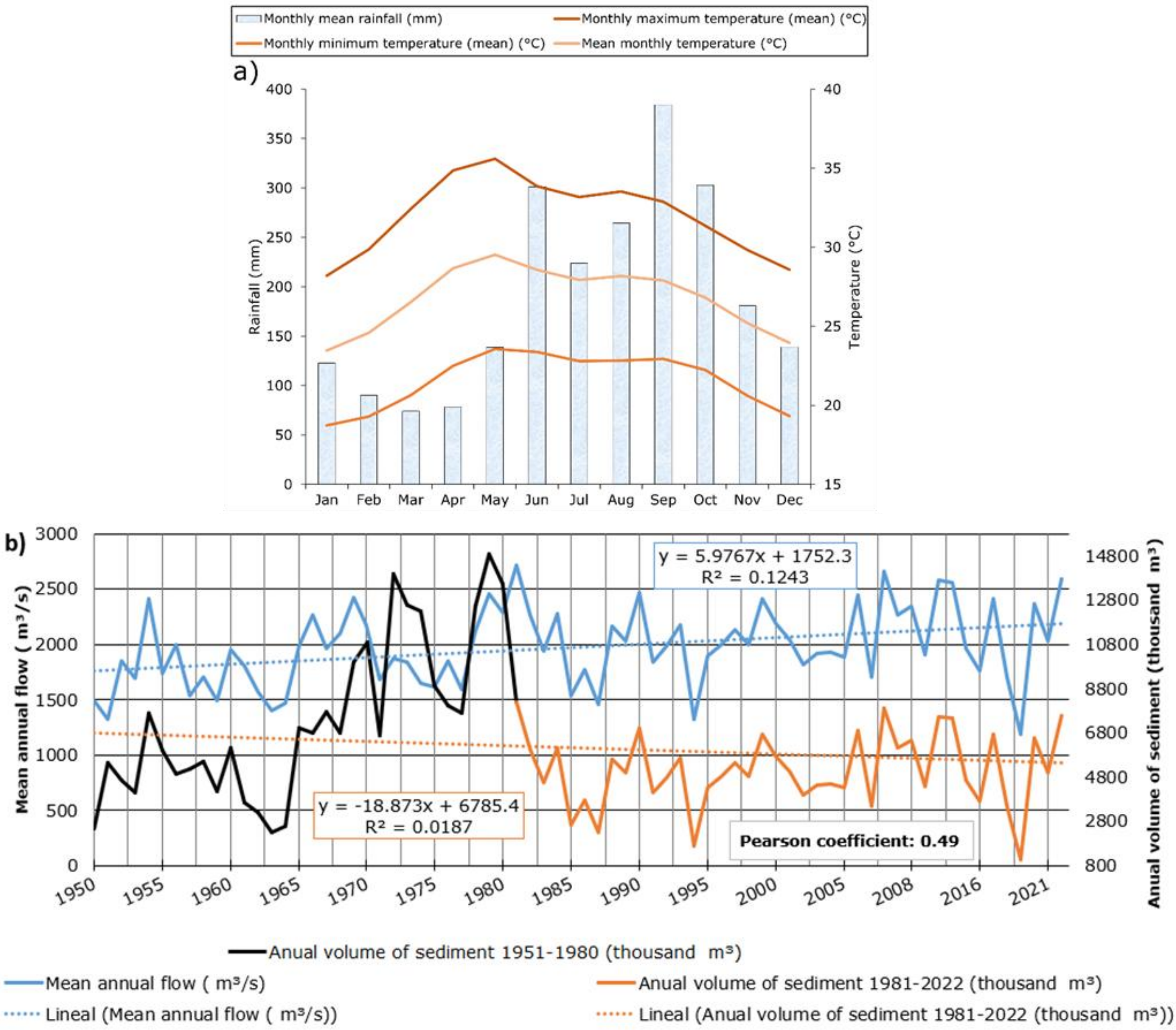

Figure 2. a) Monthly variation in temperature and rainfall pattern (station code: 27004); and b) annual water discharge (m^3/s) and sediment volume (thousand m^3) at the Boca del Cerro station (30019). **Note**: a) Linear regression values: y = mx + b; m: 4.67; Intersection b: −4,500; Volume of sediment = 4.67 × Mean annual flow − 4500; b) The annual sediment volume data in the black line represent the data measured by CONAGUA at the hydrometric station of Boca del Cerro, code: 30019 (1951-1980), and the orange line represents the data estimated by linear regression (1981-2022). The trend line, its equation, and Pearson's coefficient were calculated for the complete data period.

2. Materials and Methods

2.1. Satellite image acquisition

We consulted the images available from the Google Earth Engine from the Landsat 1-5 Multispectral Scanner (MSS), Landsat 4-5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) + Thermal Infrared Sensor (TIRS) sensors and selected the years with the highest number of images. Annual mosaics were generated for 1986 and 2019 using the median of the pixels of the available scenes with 70% of the scene free of clouds to homogenize the images and reduce the variation of the temporality of the water bodies. The R-G-B (Red, Green, Blue), near-infrared (NIR), shortwave infrared 1 (SWIR 1), and shortwave infrared 2 (SWIR 2) bands were stacked. To understand the trend in river migration, we analyzed the years obtained using the overall period (1986-2019).

2.2. Obtaining the main channel and the river centerline

The delimitation of the main channel of the UR was generated by calculating the Normalized Difference Water Index (NDWI), developed mainly to delineate water features in satellite images, eliminating soil and terrestrial vegetation characteristics (McFEETERS, 2007). The formula used is as follows:

$$NDWI = (Green - NIR)/(Green + NIR)$$

where Green is the green band, and NIR is the near-infrared band.

The index results in values ranging from -1 to 1, with values closer to 1 indicating a higher water or moisture content. Once the water bodies were identified, those bordering the main channel were vectorized and eliminated from the resulting polygons. Edge correction was applied to the main channel polygon to remove the pixel effect after vectorization. The centerline was used for lateral migration analysis, which was calculated using the Collapse Dual Lines to Centerline tool in ArcGIS. First, it identifies pairs of lines parallel to the riverbed, and then calculates the distance between these lines. Finally, the tool calculates the centerline equidistant from both parallel lines, generating a new simplified linear entity (ESRI, 2012; 1996).

2.3. Migration and channel width analysis in transects

Channel migration is measured as the lateral change in channel centerlines (HOOKE, 1987). To analyze this migration, we used an application developed by the Washington Department of Ecology, called The Channel Migration Toolbox. This application contains four tools that help automate the measurement of channel migration rates and is specifically applicable to ArcGIS® geographic information system (GIS) software. Tool 1 measures the channel migration distance along a channel reach for a given historical period. Tool 2 generated transects that were evenly spaced and perpendicular to the river centerline. The transects were constructed with a spacing of 500 m between each transect and a length of 1,400 m. Tool 3 calculates the lateral migration of the channel centerlines by calculating the variation in the centerline with the intersection for each transect generated above. Finally, Tool 4 measures the channel width along the transects, which allows us to determine changes in river dynamics, for more details of the tool consult (LEGG et al., 2014).

The segments obtained from the intersection were classified into three categories based on the average migration of each segment (Table 1). Migration categories were generated according to the significance of the values represented for total river extension. The variation in the channel width in each year of the study was generated by the intersection of the channel boundary for each year and the transect.

Table 1. Reference values of the degree of migration and sinuosity index (SI) for the classification of the Usumacinta River segments according to the total average of the channel.

Classification*	Mean total migration (m)	SI Values of (ROCHA, 2018)
Low	< 50	< 1.3
Medium	> 50	> 1.3
High	> 200	> 2

For the purposes of this study and considering the lack of previous research on lateral migration in the Usumacinta River, lateral migration was categorized into low, medium, and high. This classification was based on the knowledge of the area and observations made during the field trips. It should be noted that these values are approximate and may vary depending on the specific conditions of other rivers in different geographic environments.

2.4. Statistical Analysis

Statistical methods were employed to evaluate the relationship between the channel width and time. The analyses were performed using R software (R CORE TEAM, 2023), utilizing base functions such as the *cor.test* for correlation analysis, *aov* for ANOVA, and *Tukey's HSD* for post-hoc testing. A volcano plot was generated using *the ggplot2* package (WICKHAM, 2016) to visualize significant changes in the channel width between 1986 and 2019 for each measured transect. The Log2Ratio was calculated to evaluate how the total migration changes in relation to changes in channel width:

$$\text{Log2Ratio} = \log_2 \frac{\text{Difference in Channel Width 2019-1986}}{\text{Total Migration}}$$

This relationship can be interpreted as follows:

1. A Log2Ratio of 0 indicates equal values for the channel width and total migration.
2. A positive Log2Ratio suggests that an increase in channel width correlates with an increase in total migration.
3. A negative Log2Ratio indicates that an increase in channel width is associated with a decrease in total migration.

In addition, a scatter plot was generated using *the ggstatsplot* package (PATIL, 2021) to illustrate the relationship between the channel width in 2019 and total migration for the middle and lower basins.

2.5. Sinuosity and slope

The hydraulic factor, the Sinuosity Index (SI), was determined. SI was measured along the entire UR as a general value and was also determined by portions of the basin (middle and lower). This was calculated as follows:

$$SI = LC/LV$$

where LC is the channel length, and LV is the center valley length (BRICE, 1964), with reference values based on the sinuosity level (Table 1).

The slope calculations were performed using the ArcMap slope tool. The slope tool identifies the value in each cell of a digital terrain model (DTM) obtained from INEGI (2013). The lower the slope value, the flatter the terrain; the higher the slope value, the steeper the terrain. To calculate the slope of the main channel, a buffer of 500 m was considered using the DTM with a spatial resolution of 15 × 15 m (INEGI, 2013).

3. Results

3.1. Migration of the Usumacinta River

The migration of the main channel of the UR over the last 33 years (1986-2019) has been dynamic along the channel. We analyzed 1,458 transects, of which 91% recorded migrations of less than 50 m, classified as low migration, and only 0.61% of the transects corresponded to migrations greater than 200 m (high migration). Transects 205 and 86 had the highest migrations of 474 m and 403 m, respectively (Figure 3), adjacent to the municipality of Benemérito de las Américas in Chiapas, which belongs to the middle basin of the UR (Figure 4). In the lower basin, the greatest migration occurred in the area near the municipality of Emiliano Zapata in the state of Tabasco, in transects 900 and 902 at 220 and 167 m, respectively (Figures 3 and 4).

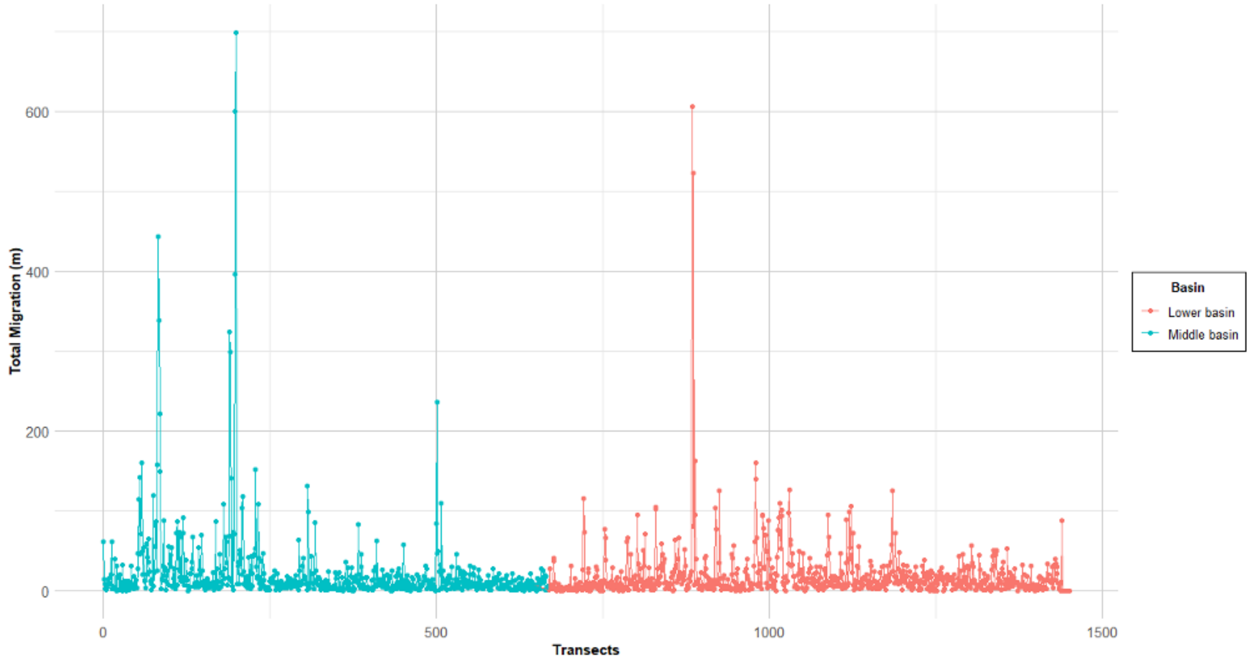

Figure 3. Lateral migration of 1,458 transects of 1,400 m of the Usumacinta River during the period 1986-2019.

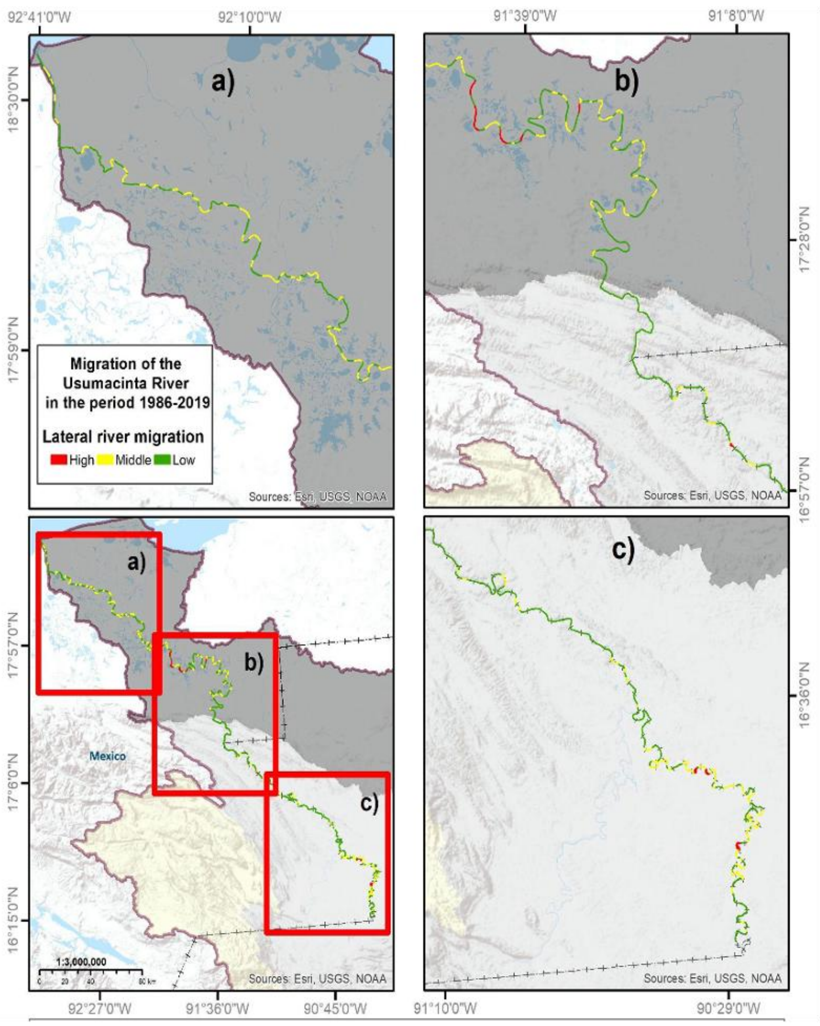

Figure 4. Distribution of migration zones in the Usumacinta River: a) and b) lower basin (dark gray); c) middle basin (light gray).

3.2. Channel Width

The channel width of the UR showed remarkable dynamics between transects but was temporarily stable between periods. In the period 1986-2019, increases in channel width were recorded for 679 transects (47%), with values up to 516 m at most, and the largest recorded increases were visible towards the middle basin at transects 515 and 1458. The remaining 779 transects (53%) exhibited a decrease of up to 144 m.

Statistical analysis of the morphological changes in rivers revealed a strong significant correlation ($r = 0.941$, $p < 0.001$) between the studied variables (channel width from 1986 to 2019). This indicates that as one variable changes, the other tends to change in the same direction, suggesting a robust relationship between the channel width and time (Figure 5a-c).

Analysis of variance (ANOVA) demonstrated significant differences among at least one of the groups ($F = 1127.943$, $p < 0.001$). This finding implies that changes in river morphology vary significantly between the middle and lower basins. Specifically, the Tukey post-hoc test indicated a significant difference in the channel width between these two basins (Tukey difference = -201.908, 95% CI = [-213.701, -190.115], $p < 0.001$). Notably, the middle basin exhibited a significantly larger channel width than the lower basin (Figure 5; Table 2). Table 2 summarizes the results of the correlation analysis, ANOVA, and Tukey post-hoc test, providing critical insights into how river morphology varies across different basins and highlighting the strong correlation between channel width and time.

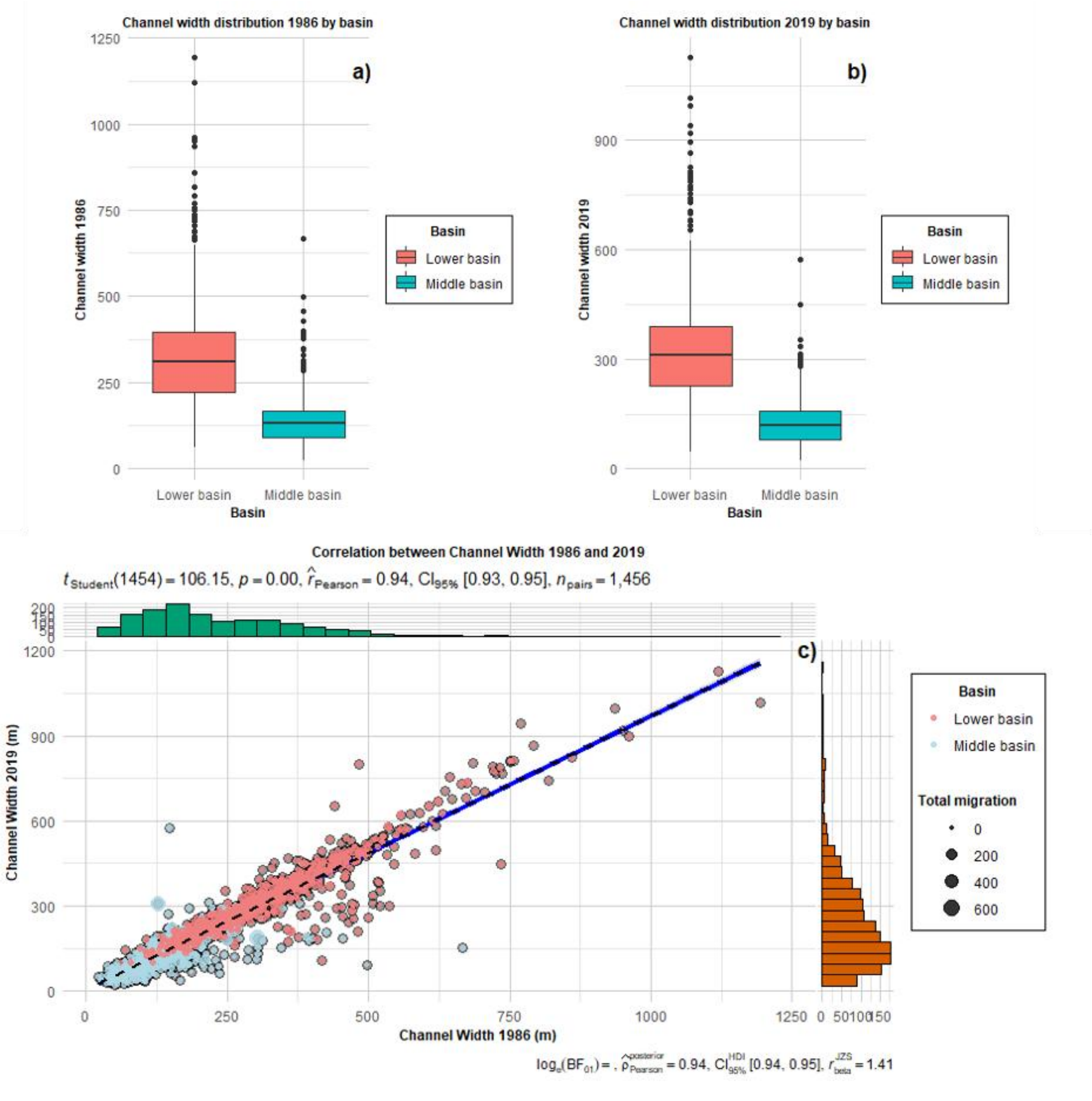

Figure 5. Comprehensive Analysis of Channel Width and Migration: Channel Width Distribution 1986 (a) and 2019 (b), and correlation between Channel Width 1986-2019 (c).

Table 2. Results of correlation analysis, ANOVA, and Tukey's post-hoc test.

Correlation

	Correlation coefficient	p_value
cor	0.941	0.001

ANOVA

Term	anova_statistic	anova_p_value
Basin	1127.943	0.001
Residuals	NA	NA

Tukey

comparison	tukey_diff	tukey_lwr	tukey_upr	tukey_p_adj
Middle Basin-Lower Basin	-201.908	-213.701	-190.115	0.001

Figure 6 presents a volcano plot showing significant changes in the channel width between 1986 and 2019, which identifies each measured transect. Therefore, it allowed us to observe how channel width varied in different sections of the Usumacinta River, highlighting that the transects located in the upper-right quadrant experienced a significant increase in their width. A significant decrease was observed in the lower left quadrant. In this context, the Log2Ratio shown in Figure 6 represents logarithm base 2 of the relationship between the difference in channel width from 2019 to 1986 and total migration. This value is used to evaluate how the total migration changes in relation to changes in the channel width.

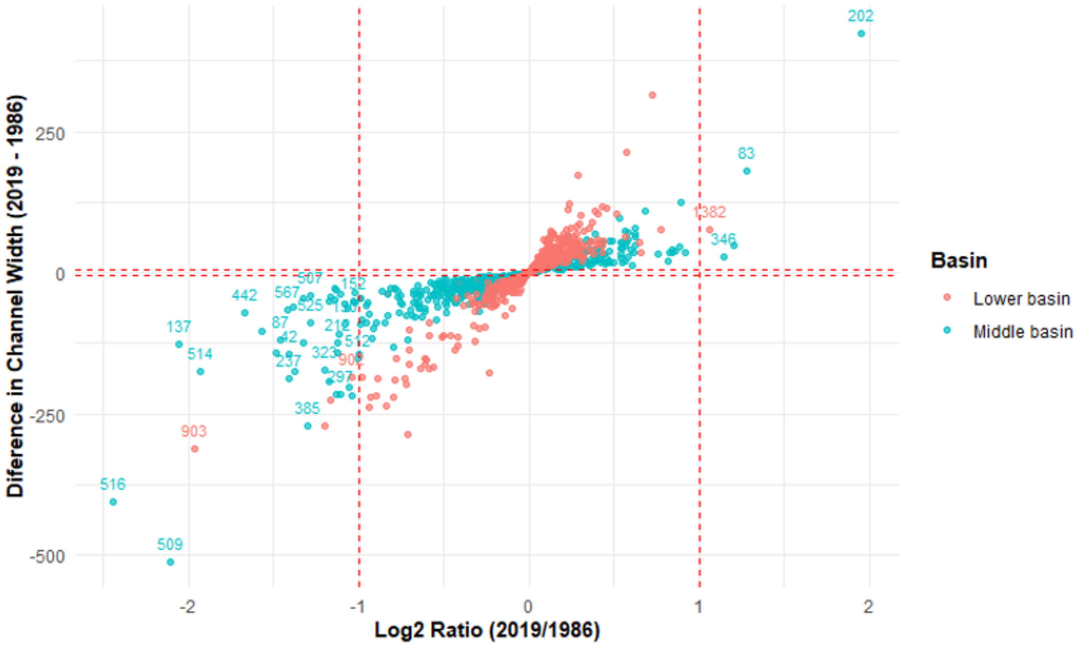

Figure 6. Volcano Plot of Channel Width 1986-2019.

In addition, the analysis of the relationship between channel width in 2019 and total migration showed significant differences between the middle and lower basins (Figure 7). In the middle basin, the slope was positive, indicating that a greater channel width correlated with an increase in total migration (Figure 7a). However, in the lower basin, the trend line indicates a negative slope, suggesting that an increase in the channel width was associated with a decrease in total migration (Figure 7b).

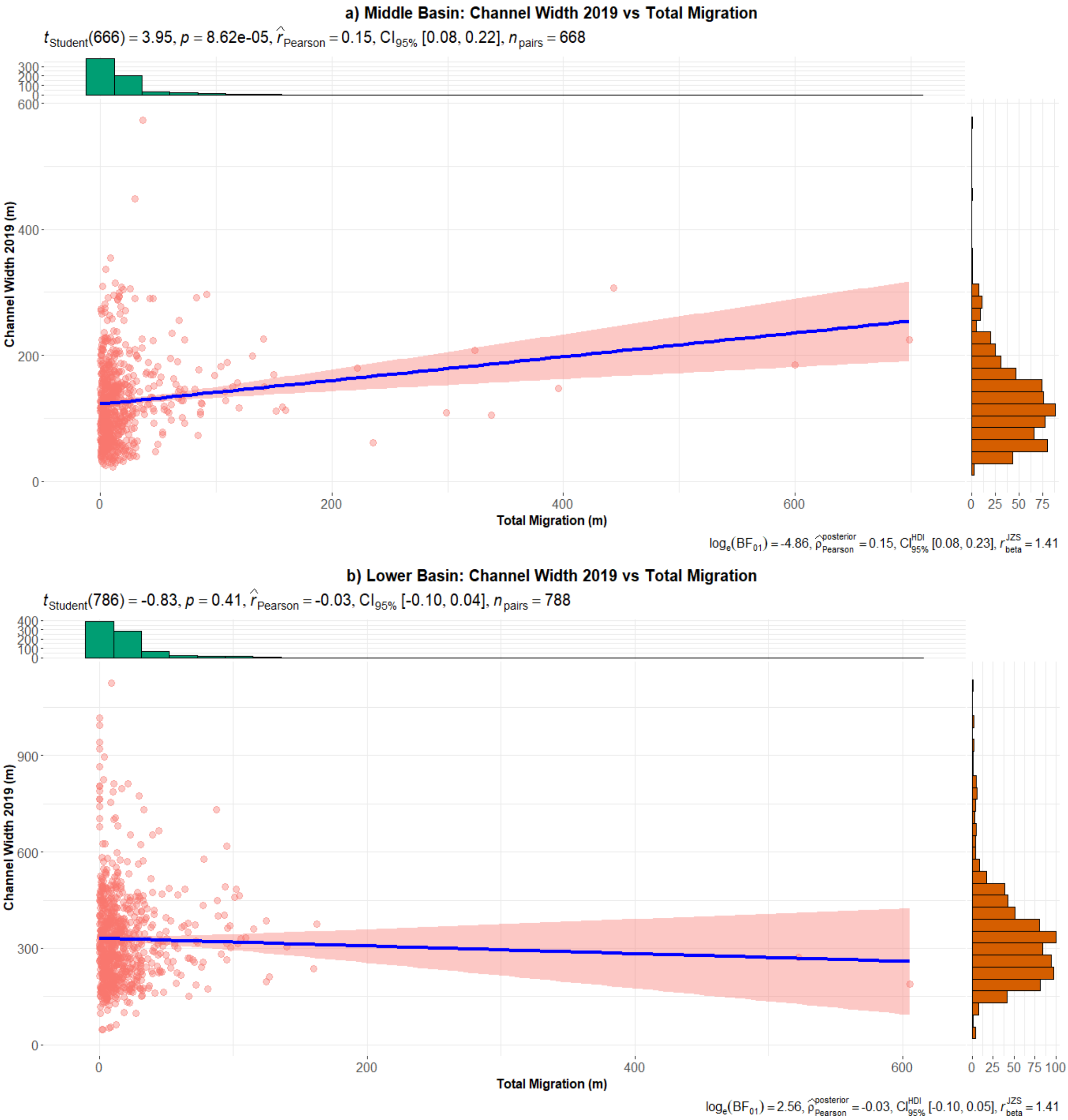

Figure 7. Scatter plot with linear regression: Channel width 2019 vs. total migration by the middle (a) and lower (b) basins.

3.3. Sinuosity and Slope

The sinuosity of the UR registered a value of 2.01 belonging to a sinuous meandering river, which translates to a river with curves in the middle-lower part of its course. Areas with high channel migration were also those with a greater presence of meanders. In addition, the sinuosity of UR was higher in the lower basin (2.13) than in the middle basin (1.83).

The slope of the main channel of the UR varies between portions of the basin. The lower basin registered a slope ranging from 0° to 59°, whereas the middle basin registered a slope ranging from 0° to 84°. It is worth mentioning that the slopes in the areas with the highest degree of migration, both for the middle and lower basins, were found to range between 0° and 15°.

4. Discussion

The analysis of 33 years of satellite imagery revealed that the Usumacinta River (UR) has undergone relatively minor changes in shape and course compared to other large alluvial rivers such as Mississippi and Paraná over similar or shorter time periods (BIEDENHARN; THORNE; WATSON, 2000; STEVAUX; MARTINS; MEURER, 2009). This suggests that the UR maintains a relatively stable planform, with 91% of the 1,458 transects exhibiting low lateral migration rates along the centerline. However, nine segments showed high migration exceeding 200 m, indicating localized areas of significant change. These results indicate that the behavior of the river varies according to the structural factors that unequally affect a certain portion of the river (QUINTANA COBO, 2015).

Remnant paleochannels visible in satellite imagery further suggest that the UR has experienced higher dynamics in certain reaches, such as near the municipalities of Benemerito de las Americas and Emiliano Zapata (Figure 5). This spatial variability in migration rates is common in meandering rivers and may be attributed to factors such as bank erodibility and local flow hydraulics, which can vary significantly along the channel. Neck and chute cutoffs are two key processes that can drive localized episodic changes in meandering river planforms. While neck cutoffs tend to occur in highly sinuous bends and develop gradually over time, chute cutoffs can form more rapidly in bends with lower curvature, often triggered by high flows interacting with specific bed topographies and floodplain characteristics. The remnant paleochannels observed may represent the legacy of such cutoff events (GAO; LI, 2024).

Understanding meander cutoff processes is fundamental for informing adaptive river management strategies that address anthropogenic pressures and environmental changes. Developing models that integrate cutoff dynamics with other factors, such as channel width variation and the impacts of episodic bank collapse events, can significantly improve the ability to predict the future morphodynamic evolution of these fluvial systems (GAO; LI, 2024). Meander cutoffs also have important implications for habitat connectivity and river ecology. By leaving oxbow lakes behind, cut-offs create unique perifluvial habitats with distinctive biodiversity (AMOROS, 2001; STELLA et al., 2011).

The relatively stable planform of the UR over the study period may be partly attributed to the fact that it remains a free-flowing river unaffected by dams (BOOTH et al., 2004; OLLERO-OJEDA; BALLARÍN FERRER; MORA MUR, 2006; MARTÍN-VIDE et al., 2012). Maintaining the natural flow regime is critical for preserving the geomorphic and ecosystem integrity of the UR because damming can disrupt sediment transport processes and impact both upstream and downstream areas (AMEZCUA et al., 2007). However, human settlements along UR banks likely influenced local hydrodynamics and bank stability (PETRICH, 2018; RIVIÈRE-HONEGGER et al., 2022; SOLÍS-CASTILLO; TERANISHI-CASTILLO, 2022).

Sediment accumulation and extraction sites (National Commission Water, CONAGUA, Spanish acronym) were observed in areas that experienced the greatest changes in the channel shape (Figure 8). Channel migration is closely linked to the size, quantity, and concentration of the sediment supplied to the river, which affects its capacity to transport sediment and alter geomorphic processes (POZO et al., 2009; PARKER et al., 2011; OLSON et al., 2014; GARCÍA-LORENZO; CONESA-GARCÍA; PÉREZ-CUTILLAS, 2015; ABBOTT et al., 2018; ZHANG; FENG; CHEN, 2020). The Observatory of the Usumacinta River Sediments, recently established as part of a sediment monitoring project, aims to implement an adaptive governance framework for the basin (CHARRUAU et al., 2022; MONZÓN-ALVARADO et al., 2022). Integrating morphological monitoring of UR into this system could provide valuable insights into the linkages between sediment dynamics and planform changes over time.

In summary, these results suggest a clear variability in the morphodynamics of the Usumacinta River, with significant differences that may be influenced by environmental, geomorphological, and anthropogenic factors. The strong correlation observed and the significant differences in channel width between the middle and lower basins indicate that it is essential to consider these factors in future studies to better understand the implications of river morphology and their associated ecosystems.

The meandering and sinuous characteristics of UR, with higher sinuosity and lower slopes in the lower basin than in the middle basin, promote lateral migration and make the river more dynamic overall (OLLERO-OJEDA, 1990; SOLÍS-CASTILLO et al., 2013a, 2013b; CEBALLOS-LÓPEZ, 2011; KONRAD, 2012; QUINTANA COBO, 2015; BASILE, 2018). Topographic and sedimentological controls alter the course of meandering rivers confined to alluvial plains (CONESA-GARCÍA, 1992), with sinuosity often increasing as slope decreases downstream (GONZÁLEZ, 2017). However, the relatively stable planform of UR over the study period suggests that these intrinsic factors have not driven major changes in the recent decades.

The processes of cross-circulatory flow and convective redistribution of longitudinal flow velocity significantly influence the morphodynamics of meandering rivers, such as Usumacinta, affecting sediment transport and channel evolution. The relative importance of these processes depends on the width-to-depth (B/h) ratio of the river. For B/h greater than 9, the flow is dominated by a classical cross-circulatory cell that strengthens with increasing flow depth. In contrast, for B/h ≤ 9, an outer bank cell emerges, altering the overall flow structure and sediment dynamics (CHENG; LI, 2024). Understanding these flow patterns is critical for predicting the erosion and deposition patterns in meandering systems.

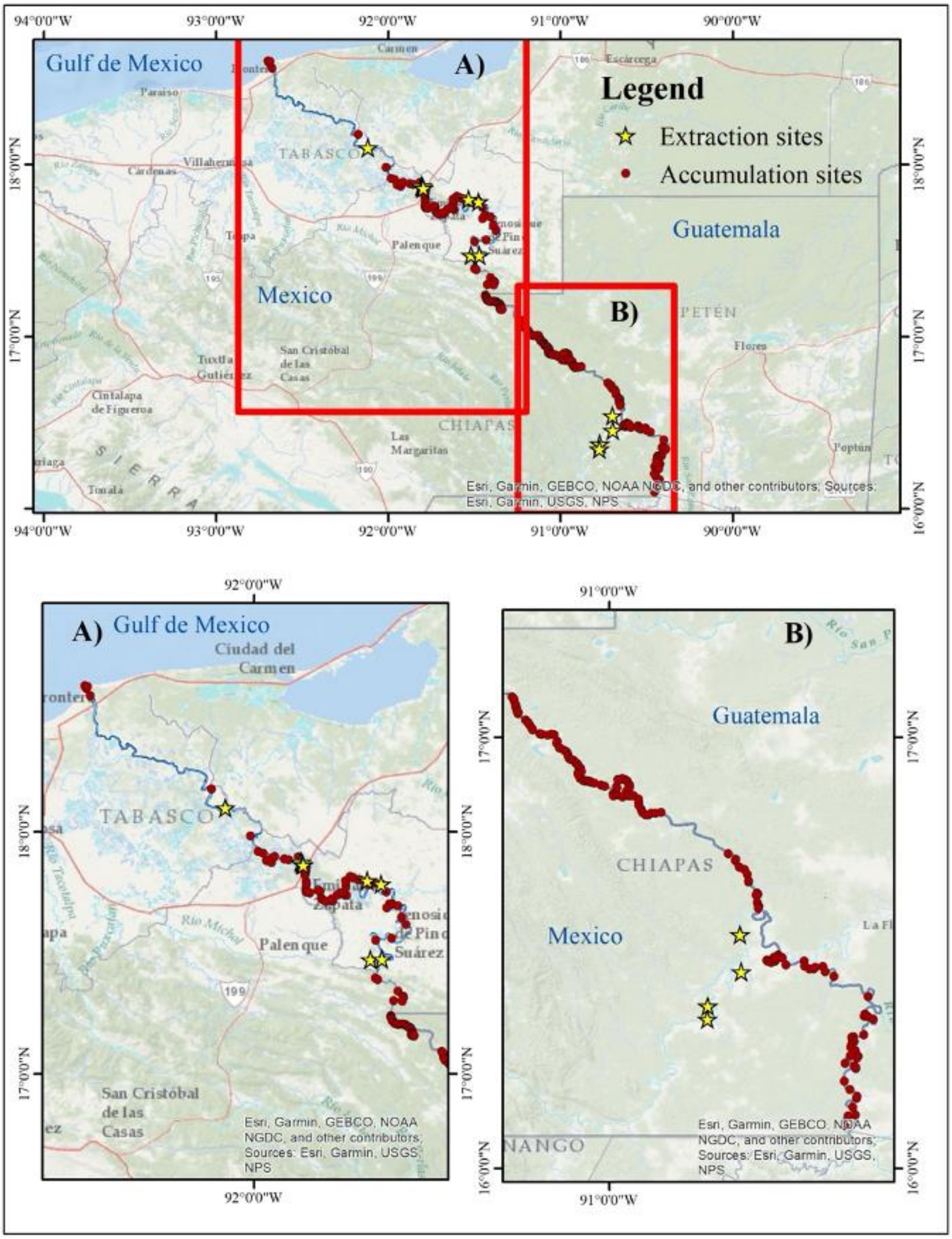

Figure 8. Sediment accumulation and extraction sites in the Usumacinta River.

In summary, the Usumacinta River has exhibited a relatively stable planform over the past 33 years compared to other large alluvial rivers, likely due to its free-flowing nature and lack of major human alterations. However, localized areas of significant migration and the presence of remnant paleochannels indicate that the river has experienced episodic planform changes, potentially driven by processes such as neck and chute cutoffs that are common in meandering systems (GAO; LI, 2024). Gao et al. (2024) provided insights into how tidal cutoffs, characterized by bidirectional currents, maintain hydrological connectivity with parent channels, which may parallel some of the dynamics observed in Usumacinta. Their findings suggest that hydrodynamic processes in tidal environments can differ significantly from those in fluvial systems, highlighting the need for continued monitoring of UR morphodynamics. Specifically, this study emphasizes that tidal cutoffs are less likely to disconnect from parent channels due to frequent overbank events, which can keep them active by flushing away fine-grained sediments. Therefore, the ongoing monitoring of UR morphodynamics, integrated with the Observatory of the Usumacinta River Sediments monitoring efforts, can shed further light on the drivers and implications of planform changes in this important river system. Incorporating knowledge of the cross-circulatory and convective flow processes that shape meandering rivers (CHENG; LI, 2024) can further enhance our understanding of UR evolution, particularly regarding how these processes influence sediment transport and channel stability.

In this context, meander cutoffs can also have potential geopolitical implications, especially in rivers that serve as international borders, such as the Usumacinta between Mexico and Guatemala. When a cutoff substantially changes the course of a river, it can alter the delineation of borders between countries or regions, potentially leading to disputes over river boundaries (HOOKE, 1995). Therefore, although no dramatic course changes were observed in Usumacinta during the study period, managers should be alert to the possibility of future meander cutoffs that may have implications for border delineation. Moreover, meander cutoffs can interrupt longitudinal channel continuity, fragment habitats, and affect migration patterns of fish and other aquatic organisms (HOOKE, 1995; SELIGER; ZEIRINGER, 2018). Understanding how meander cutoffs influence habitat connectivity is important for future research.

Rivers worldwide are being transformed by changes related to human activities, such as dam construction, land use change, and mining (DETHIER; RENSHAW; MAGILLIGAN, 2022; DETHIER et al., 2023). Lateral migration in river morphodynamics is considered a complex interaction driven by natural and anthropogenic factors and is a key determinant of the intensity of lateral migration and significant changes in riverbanks over time (LANGOVIĆ, 2020). Church (2015) highlighted the influence of water flow, sediment regime, and channel changes on river morphology and stability. Additionally, river width represents the best first-order predictor of riverbank erosion, whereas geology, hydrology, and human activities represent second-order influences that affect the relationship between width and bank erosion in different global river basins (LANGHORST; PAVELSKI, 2023).

From this perspective, the river systems of the Grijalva and Usumacinta Rivers have distinct geomorphological characteristics. The Grijalva River has had more anthropic intervention than the UR, and this human influence together with natural factors influenced the historical geomorphologic changes reported in this basin known as "rompidos"; as is known by the local population, the historic lateral migration and significant changes on the riverbank (MUÑOZ-SALINAS et al., 2023; 2017; MUÑOZ-SALINAS; CASTILLO, 2015). In general, Gallardo-Cruz, Fernández-Montes de Oca, and Rives (2019) reported that the intensive transformation processes that have affected the lower UR basin in recent decades are related to anthropic activities such as agricultural development plans and energy production, including oil palm cultivation and forest resources, mainly in the municipalities of Balancán and Tenosique, Tabasco. Likewise, Camacho-Valdez et al. (2022) analyzed the rapid expansion of palm oil plantations in the Usumacinta watershed and the need to guarantee the integrity of floodplain ecosystems and the provision of ecosystem services to communities. Different portions of the UB are exposed to various anthropogenic pressures in both Mexico and Guatemala, although a greater degree of pressure has been observed in the Guatemalan territory (OROZCO-ÁVILA et al., 2024; GALLARDO-CRUZ et al., 2021), which includes the middle and higher parts of the UB.

In this context of anthropogenic transformations in vegetation, according to White, Morrison, and Nelson (2023), a greater density of vegetation and larger flows can increase bedform topographic heterogeneity, which can enhance stream habitat complexity. The results of this study represent an important contribution in this sense and may be useful for decision-makers and stakeholders striving to achieve conservation, protection, and restoration of river corridors. However, the scope of this study did not include floodplain vegetation on channel-altering hydrodynamic forces, bedform topography, and sediment transport. It is necessary to continue deepening it as a future line of research, which is poorly understood and where there exists an important knowledge gap.

5. Conclusions

Morphological analysis of the Usumacinta River (UR) has revealed negligible geomorphological changes in recent times; however, satellite imagery suggests a more dynamic system over extended periods, necessitating further examination. This dynamism was primarily attributed to the free-flow regime of the river. A direct correlation was observed between sinuosity and slope variations in regions exhibiting greater lateral migration and channel width. The UR can be classified as a meandering river because of its high sinuosity along its entire length, indicating a natural inclination to diverge from a straight course, which may reflect its inherent instability. This dynamic condition suggests that specific riparian communities in areas with the greatest migration and channel width may be at risk in the future.

Therefore, we recommend implementing a comprehensive monitoring system for river morphology. This system should incorporate geological, tectonic, and edaphic factors as well as studies on sediment accumulation, flow volume calculations, and granulometry assessments. In general, this focus can be key to understanding the trends in river systems and the behavior of hydrological basins. Moreover, it is necessary to promote ongoing monitoring to develop predictive models for the risks and vulnerabilities of riparian communities. This research provides important insights for decision makers to develop and improve strategies for sustainable management of the Usumacinta River Basin. By integrating knowledge of the hydrodynamic processes that shape meandering rivers, we can enhance our understanding of UR evolution and inform future initiatives and strategies for its preservation and conservation.

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