Remote Sensing-Based Geospatial Analysis of Channel Migration Patterns in the Lower Shire Valley of the Shire River, Chikwawa District, Malawi

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Abstract. This study investigates the spatiotemporal dynamics of the Shire River's fluvial geomorphology from 1975 to 2023, focusing on channel migration, width variation, sinuosity, meander curvature, and sediment budget changes. Using multi-temporal satellite data and geospatial analysis, key indicators were quantified across 41 cross-sectional zones to evaluate morphodynamic responses over four time intervals: 1987–1975, 1999–1987, 2011–1999, and 2023–2011. Results show a progressive intensification of lateral channel migration, with several zones recording annual rates exceeding 4 m/year and R^2 values above 0.90. Channel width increased significantly, from a mean of 4.75 m to 83.64 m, confirmed by repeated measures ANOVA ($p < 0.001$). Although the sinuosity index did not change significantly ($p = 0.223$), localized trends indicated both meander amplification and channel straightening. The Radius-to-Width ratio remained consistently above 2.0, suggesting morphological stability in bend curvature. Sediment analysis revealed a shift from net erosion (–181.55 m²) in 1987–1975 to substantial net accretion (+2778.11 m²) by 2023–2011, with a strong linear trend ($R^2 = 0.90$). These morphodynamic changes are linked to climate variability, extreme floods, and anthropogenic pressures such as land use change and riverbank modification. The findings highlight the need for integrated, data-driven river management approaches to mitigate flood risks and guide sustainable development in riverine environments.

1.0 Introduction

River channel migration is a fundamental component of fluvial geomorphology, reflecting the complex interplay of hydrodynamic forces, sediment transport processes, and valley morphologies over time. This lateral shifting of river channels manifesting through meandering, avulsion, and braiding is both a natural geomorphic phenomenon and a critical concern for floodplain management, especially in densely populated or agriculturally significant regions (Giano, 2021; Gharti *et al.*, 2025). Channel migration not only redefines river morphology but also alters adjacent land use patterns, undermines infrastructure, and exacerbates flood vulnerability in low-lying terrains (Yousefi *et al.*, 2021). Over the decades, analytical approaches combining hydrological modelling, morphometric indices (e.g., sinuosity, braiding, and centerline shift), and remote observation have been increasingly used to quantify these riverine dynamics and inform sustainable watershed governance (Giano, 2021)

Recent decades have witnessed significant advancements in the use of geospatial technologies namely, Geographic Information Systems (GIS) and Remote Sensing (RS) in mapping and monitoring river migration at multiple spatial and temporal scales. These technologies have enabled detailed assessments of fluvial processes such as bank erosion, sediment deposition, planform evolution, and the delineation of channel migration zones (CMZs), especially where historical aerial photographs or field data are sparse (Pal and Pani, 2019). Numerous studies across Asia, Europe, and North America including on the Ganga, Brahmaputra, Yellow, and Mississippi rivers have employed multi-date satellite imagery to analyse spatial-temporal changes in river course, identify erosion-prone zones, and model flood risk due to dynamic fluvial behaviour(Yang *et al.*, 2015; Mondal, Thakur and Bandyopadhyay, 2020; Nones, 2021; Gharti *et al.*, 2025). In such contexts, high-resolution datasets, coupled with change detection techniques, have proven valuable in identifying migration rates, channel width variability, and geomorphic drivers such as land use change, deforestation, precipitation variability, and upstream dam regulation.

Despite this growing body of work, systematic studies on river channel migration in Sub-Saharan Africa remain limited. In Malawi, the Shire River originating from Lake Malawi and draining into the Zambezi River is the country's largest and most ecologically and economically significant river system (Banda *et al.*, 2020; Mtilatila *et al.*, 2020). Traversing the flood-prone Chikwawa District in southern Malawi, the river supports critical sectors including agriculture, hydropower generation, fisheries, and biodiversity conservation. However, the Shire River is also highly dynamic, showing pronounced lateral shifting and floodplain expansion over the past four decades. These shifts have been exacerbated by intense seasonal rainfall, high sediment loads, upstream deforestation, and anthropogenic land-use pressures, resulting in accelerated bank erosion, displacement of rural settlements, and destruction of agricultural land (Šakić Trogrlić1 *et al.,* 2017; Garcin, Mdala and Kalebe, 2025). Cyclonic events such as Cyclone Freddy in 2023 have further intensified these risks by contributing to abrupt morphological changes and infrastructure vulnerability.

Existing studies on the Shire River have largely concentrated on hydrological regimes, aquatic ecosystems, and flood modelling, with limited attention to long-term planform dynamics and lateral migration trends. This has left a critical gap in the understanding of how the river's geomorphic behaviour intersects with climate risks and human exposure, especially in a district like Chikwawa that frequently ranks among the most disaster-prone in Malawi. Addressing this gap is essential, not only for advancing the scientific knowledge of African fluvial systems but also for informing policies related to floodplain zoning, land tenure, infrastructure development, and climate adaptation. This study, therefore, seeks to investigate the spatial and temporal patterns of channel migration along the Shire River in Chikwawa District using multi-date satellite imagery and GIS-based analytical tools. By quantifying channel shifts over a 39-year period and delineating zones of erosion, deposition, and channel instability, this research contributes to a deeper understanding of fluvial dynamics in tropical, sediment-laden rivers under the pressures of both natural processes and anthropogenic change. The analysis of morphometric indicators such as centerline displacement, channel width variability, and sinuosity is complemented by field validation and participatory insights, offering a comprehensive perspective on the drivers and consequences of channel migration. In doing so, the study aims to support disaster risk reduction and river corridor management in one of Malawi's most ecologically and socioeconomically vulnerable regions.

2.1 Study Area

This study was conducted along a section of the Shire River, the largest and only outlet of Lake Malawi, which flows southward through the southern region of Malawi before joining the Zambezi River in Mozambique. Geographically, the study area is located within Chikwawa District, falling approximately between 16°00′–16°30′ South latitude and 34°45′–35°15′ East longitude. The Shire River traverses a floodplain-dominated landscape in this region, draining a vast catchment that includes upper highland plateaus and low-lying alluvial plains. The total length of the river is about 402 km, but this study focused on a 75-km reach of the Shire River, extending from the Kapichira Hydropower Station through the confluence with the Mwanza River to boundary of Chikwawa District, a stretch known for seasonal flooding, and significant land use change (USAID, 2023; Bossa *et al.*, 2024).

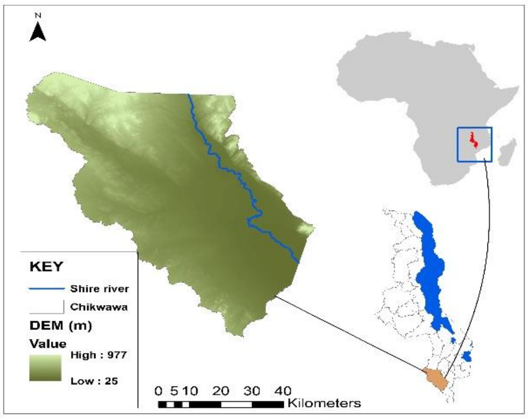


Figure 1. Map of Chikwawa District

2.1.2 Climate and Geology of the Shire River

The Shire River exhibits a wide range of fluvial morphological behaviour in its lower reach through Chikwawa District, shaped by seasonal climatic variability, basin geology, and upstream hydrological regulation. The study area experiences a tropical savanna climate with a distinct wet season (November to April) and dry season (May to October). The average annual precipitation ranges between 900 mm and 1,200 mm, with more than 85% falling during the monsoon period (Nakapu *et al.,* 2023). As shown in Fig. 2, annual peak discharge has demonstrated an upward trend over the past three decades, reflecting increasing hydro-climatic extremes attributed to climate change. Hydrological data from the Global Flood Detection System (GFDS), Station No. 123, reveal that peak river discharge in the Shire River has exceeded 17,700 m^3/s during major flood events surpassing established danger thresholds and causing widespread inundation of low-lying areas. These extreme discharge events highlight the complex interplay between climatic variability, geomorphological processes, and river channel dynamics in the Chikwawa District. The recurrent exceedance of flood thresholds, combined with highly erodible soils and mounting land-use pressure, underscores the urgent need for spatially explicit analyses of river migration patterns. Such assessments are critical for informing adaptive land-use planning, sustainable agriculture, and effective disaster risk reduction strategies in this flood-prone region.

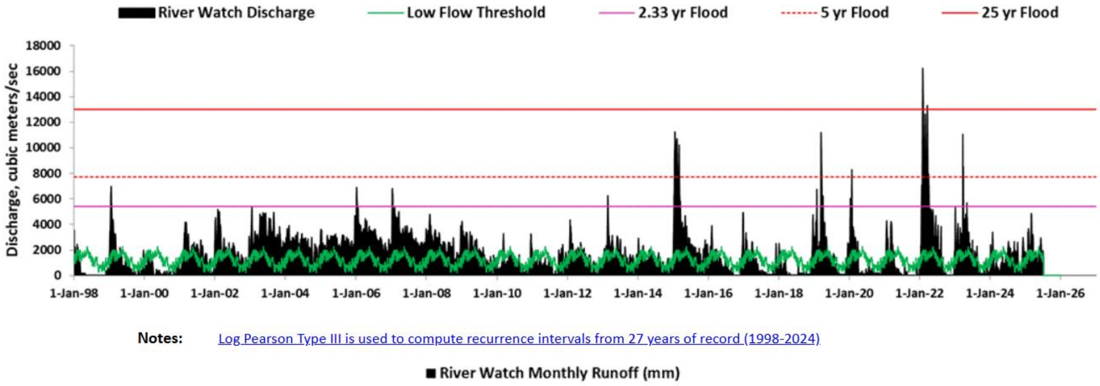


Figure 2. The flood frequency analysis, 1998 to 2024 Source: floodobservatory.colorado.edu/SiteDisplays/56.htm

2.2 Methodology

2.2.1 Dataset Preparation

This study employed integrated Remote Sensing (RS) and Geographic Information System (GIS) techniques to analyse the spatial and temporal channel migration of the Shire River from 1975 to 2023. Multi-date satellite imagery and supporting environmental datasets were acquired and pre-processed to extract relevant fluvial features and assess river dynamics. Specifically, Landsat imagery from the United States Geological Survey (USGS) https://earthexplorer.usgs.gov/.

Collection 2 Level 2 and 1 archive was utilized, comprising datasets from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI), and Landsat 9 OLI-2 sensors. These images correspond to Path 168/ Row 071, covering the study stretch of the Shire River in Chikwawa District. Eight cloud-free Landsat scenes were selected at five-year intervals from 1975 to 2023, along with a recent image from 2023, to capture planform shifts and channel morphology changes over a 43-year period. The selected images, detailed in Table 1, were chosen during the post-rainy season (September–November) to minimize seasonal water fluctuations and vegetation interference. All satellite data underwent standardized pre-processing, including radiometric calibration, atmospheric correction, geometric alignment, and resampling to 10-meter resolution. The Scan Line Corrector (SLC) errors in Landsat 7 data (post-2003) were mitigated using mask-based gap-filling techniques to preserve waterbody continuity.

Table 1 Description of the data used

Image	Resolution	Date of acquisition	Path/row
Landsat 03MSS	60m	10/11/1987	168/071
Landsat 05 TM	30m	22/09/1999	168/071
Landsat ETM+	30m	10/11/2011	168/071
Sentinel-1	10m	10/10/2023	-
Topographic Image	-	1975	-

All spatial data were projected to the Universal Transverse Mercator (UTM) Zone 36S, based on the WGS 1984 datum, ensuring geometric consistency during image overlay, digitization, and change detection analysis.

3.3. 3.3. Geomorphological Analysis

To characterize the temporal and spatial evolution of river morphology, five key geomorphological indicators were employed: centerline migration trends, channel width changes, sinuosity indices, channel radius-width ratio (RWR), and erosion–accretion mapping. These metrics offer an integrated understanding of river dynamics, including planform adjustment, lateral migration intensity, hydraulic efficiency, and sedimentary processes.

3.3.1. Centerline Migration Trends

Centerline migration refers to the lateral shift of the river's central flow path over time, indicative of channel instability or planform evolution. Following the approach by Hooke, Souza and Marchamalo (2021) and recent updates by Crivellaro *et al.*, (2024), the centrelines for each time step (1975, 1987, 1999, 2011, and 2023) were extracted using the mid-distance between left and right banks. The magnitude of migration was computed by overlaying successive centrelines and measuring the perpendicular distance between them across regularly spaced cross-sections. The average migration rate (m/year) was then derived for each time interval by dividing the total lateral shift by the time span, providing insights into periods of accelerated migration or stabilization.

3.3.2. Channel Width Changes

Channel width is a primary indicator of hydromorphological response to discharge variability and sediment load. Width was measured orthogonally across 40+ fixed cross-sections from the left to right bank for each year of observation. Following methodologies outlined by Eppes *et al.*, (2010), mean channel width was calculated for each time period, and trends were analysed to detect patterns of narrowing, widening, or equilibrium conditions. Statistical comparisons were made using ANOVA and regression analysis to assess significant temporal differences in width changes (Crivellaro *et al.*, 2024).

3.3.2. Sinuosity Index

The sinuosity index (P) is a widely used metric for quantifying the degree of channel meandering, calculated as the ratio between the actual channel length and the straight-line (valley) length. As originally defined by Friend and Sinha (1993), and as reaffirmed in recent geomorphological studies (Wulder *et al.*, (2019; Franks and Rengarajan, 2023), the index is expressed as:

$$P = \frac{L_{cmax}}{L_R}$$

where L_{cmax} is the mid-channel length of the primary channel, and L_R is the straight-line distance (valley length) between the upstream and downstream ends of the reach. A sinuosity value greater than 1.5 typically indicates a meandering river, while values closer to 1 reflect straighter channel patterns.

3.3.4. Channel Radius-Width Ratio (RWR)

The radius-width ratio (RWR) integrates the curvature of meanders with the width of the channel, serving as a proxy for meander tightness and hydraulic resistance Gellens, (1991). It is calculated as:

$$RWR = \frac{R}{W}$$

where R is the radius of curvature at meander apexes, and W is the local channel width. Radii were measured by fitting circular arcs to the outer banks of selected meanders, while corresponding widths were derived from cross-sectional measurements. RWR values were classified following established thresholds: tight meanders (RWR < 2), moderate meanders (RWR = 2–4), and broad loops (RWR > 4) (Suresh *et al.*, 2022).

3.3.5. Erosion and Accretion Analysis

Erosion and accretion patterns reveal areas of bank retreat and bar deposition, respectively, reflecting sediment dynamics and flow energy. A change detection approach was applied to banklines digitized from multi-date imagery. By overlaying banklines from consecutive years (e.g., 1987 vs. 1975, 1999 vs. 1987), polygons of gain (accretion) and loss (erosion) were generated using GIS differencing tools. The net sediment budget was then calculated for each interval by subtracting total erosion area from total accretion area (Suresh *et al.*, 2022 ; Ashmore, 2013).

4.0 Results

The analysis of channel lateral migration from 1975 to 2023 was conducted using geomorphic data collected across 40 cross-sections along the river. The river centerline from the year 1975 obtained from Topographic Map was designated as the reference year, with all subsequent migration values calculated relative to it. This standardization allowed for a consistent temporal comparison of lateral channel shifts. The computed mean migration values for the years 1987, 1999, 2011, and 2023 were 9.57 m, 23.19 m, 72.23 m, and 229.35 m, respectively, indicating a substantial and progressive increase in river channel movement over the decades. The resulting regression equation, $y=4.72x+2.39$ where x is the number of years since 1975, demonstrated a strong linear relationship between time and mean migration, with a coefficient of determination $R^2=0.98$.

This high R^2 value indicates that the increase in migration is highly time-dependent, pointing toward a trend of accelerating channel dynamics. The sharp increase observed between 2011 and 2023 may reflect the combined impacts of intensified hydrological events, land use changes, and other anthropogenic influences on the river system. These findings align with existing literature on fluvial processes, which highlights that lateral migration tends to increase under conditions of climatic variability and catchment disturbances (Annayat and Sil, 2020b).

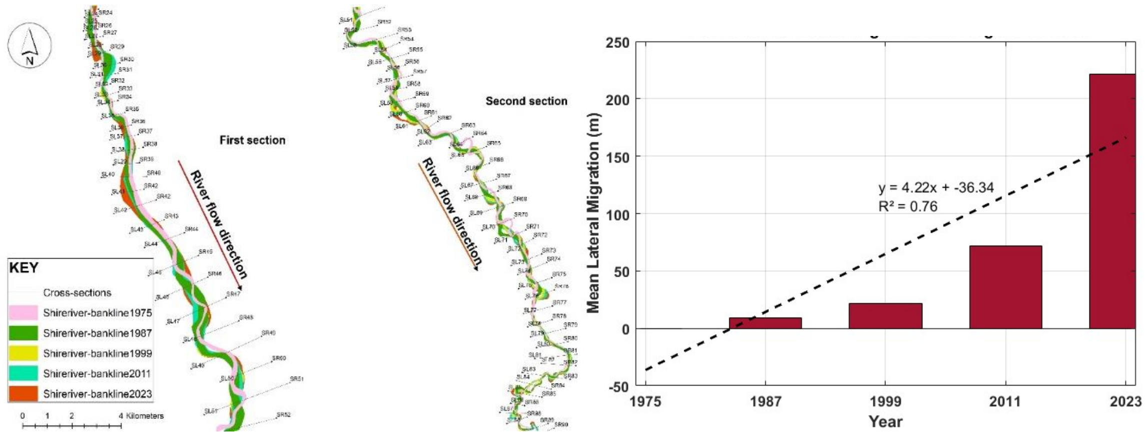
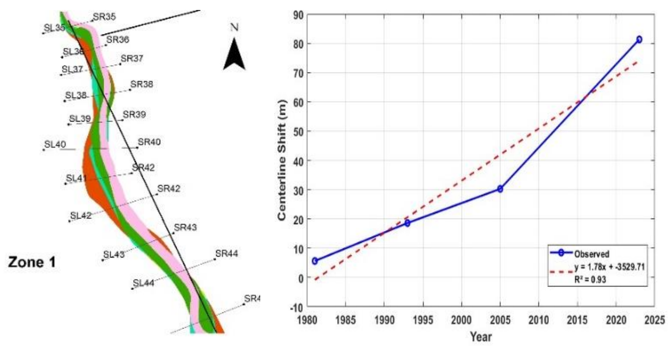


Figure 3. River channel centerline

4.1 Centerline Migration Trends of the Shire River

The analysis of channel centerline migration reveals significant spatial and temporal variability in lateral river movement across the 5 assessed zones. Using four temporal intervals—1987–1975, 1999–1987, 2011–1999, and 2023–2011—linear regression analyses indicate a consistent increase in lateral migration over time. The mean centerline shift rose from 9.6 meters in 1987–1975 to 54.2 meters in 2023–2011, underscoring a progressive intensification in channel dynamics, especially in the last decade.

Over 85% of the zones exhibited positive regression slopes, indicating that channel migration is accelerating. High migration rates were recorded in several cross sections, including Zone 3 (SR57–SL57) with a slope of 4.83 m/year (R^2 = 0.94), and Zone 1 (SR39–SL39), which experienced the largest single-interval shift of 183.06 meters between 2011 and 2023 (slope = 4.26 m/year, R^2 = 0.91). Conversely, zones like Zone 2 (SR48–SL48) displayed erratic trends with negative shifts and low model fit (R^2 = 0.36). The most intense migration was observed in the last temporal interval (2011–2023), likely driven by recent extreme weather events such as Cyclone Freddy (2023), which significantly altered fluvial energy and sediment transport dynamics in the Lower Shire floodplain. Cross sections such as SR64–SL64 and SR56–SL56 registered lateral shifts of over 150 meters in this period alone.



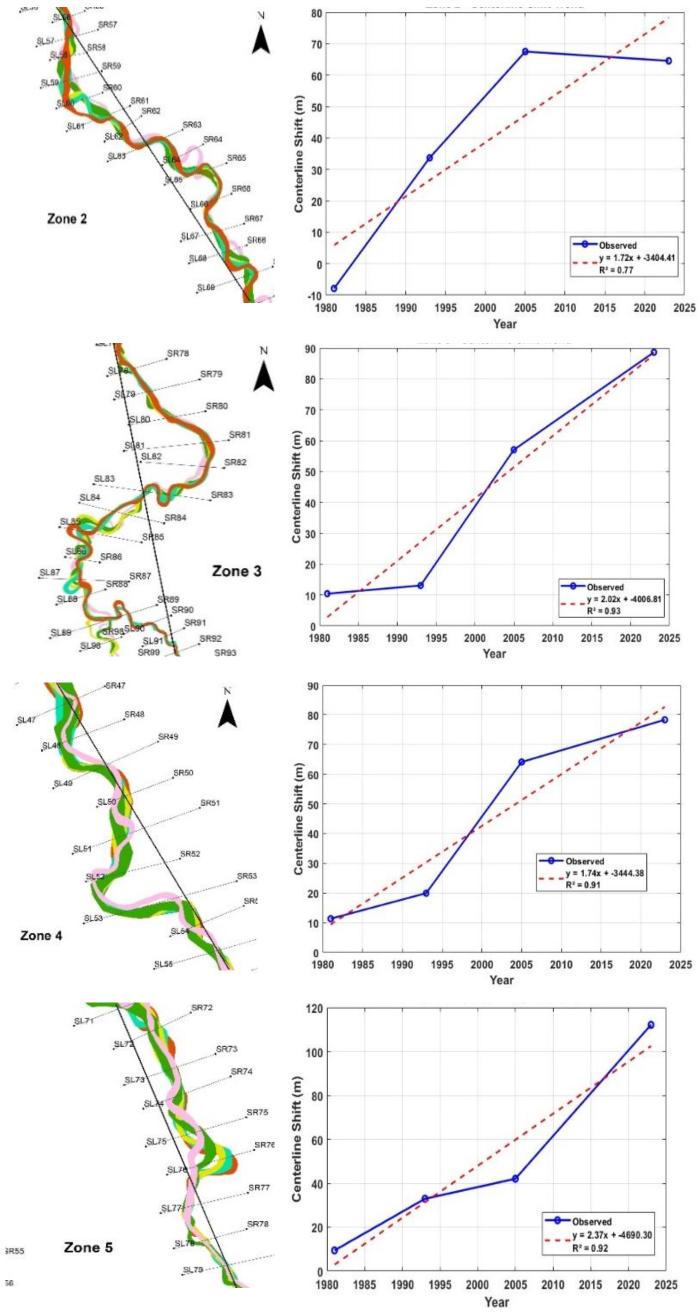


Figure4. Centerline migration rates for all five zones

Regression models confirmed these findings. Zones with high R^2 values (> 0.85) reflect stable, predictable migration behaviour. In contrast, zones with R^2 < 0.50 exhibited non-linear or chaotic migration patterns. These findings align with previous studies in tropical and subtropical systems, which report increased river migration under changing flow regimes, floodplain encroachment, and reduced channel confinement (Debnath *et al.*, 2017; Annayat and Sil, 2020b).

4.2

The temporal analysis of Shire River channel width changes reveals a pronounced and statistically significant increase in lateral channel dynamics over time. Mean channel width changes rose dramatically from 4.75 meters in the 1987–1975 period to 83.64 meters in the 2023–2011 interval. an overall increase of over 1,660% relative to the baseline. A repeated measures ANOVA confirmed a significant temporal effect on channel width (F, $p < 0.001$), suggesting that the observed changes are not random but rather indicative of systematic fluvial adjustment. Post hoc comparisons revealed that the most significant jump occurred between 1999–1987 and 2011–1999 ($t(39) = -5.26$, $p < 0.001$), while other transitions did not reach statistical significance. This rapid expansion in channel width corresponds with the increasing frequency and intensity of extreme hydrometeorological events in recent decades, consistent with findings from other river systems under climate-driven hydrological stress (Annayat and Sil, 2020a; Baniya *et al.*, 2023). These results reinforce earlier conclusions that tropical and subtropical rivers are highly responsive to external forcing mechanisms and require ongoing geospatial monitoring to guide risk-informed management of floodplains and riparian infrastructure (Lagasse, Schumm and Zevenbergen, 2004; Chakraborty and Mukhopadhyay, 2015).

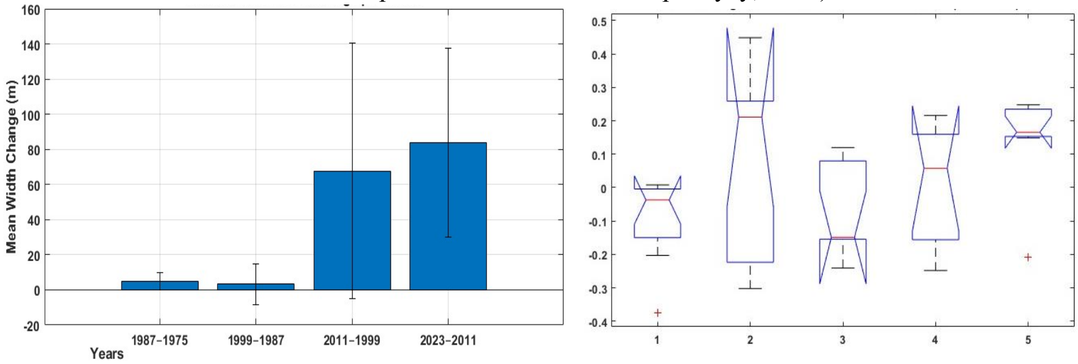


Figure 5. Channel width changes

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The sinuosity index analysis revealed important spatial and temporal variations in channel morphology. Although overall average sinuosity remained relatively high indicative of a meandering system descriptive statistics showed a noticeable decline in 2011 (mean = 1.680), followed by recovery to 2.167 by 2023. Despite visible trends, a one-way ANOVA indicated no statistically significant difference in sinuosity across time points ($F(4, 20) = 1.570$, $p = 0.223$), suggesting resilience in planform structure or the need for higher-resolution temporal and spatial data (Rashid, 2020). Regression-based classification showed that Zones 3 and 5 experienced increasing sinuosity, Zone 2 remained stable, and Zones 1 and 4 showed declining trends.

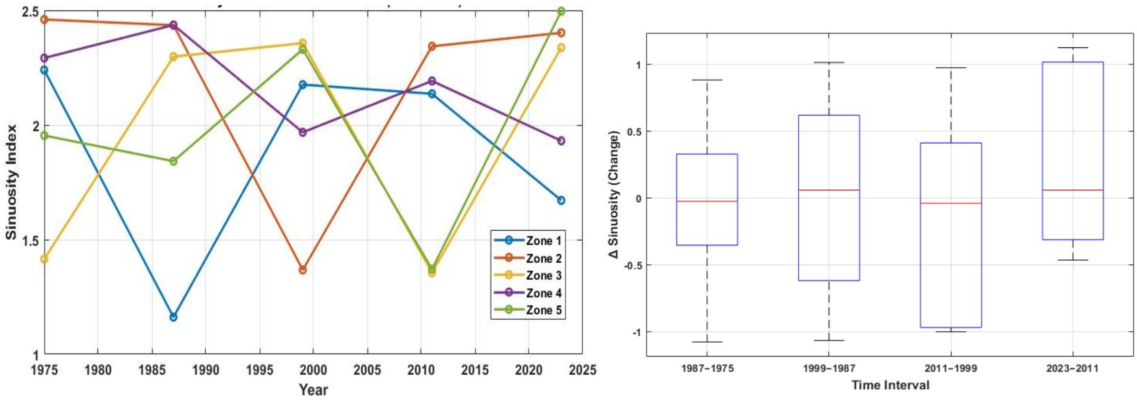

Figure 6. Sinuosity indices

4.4 **Channel radius width ratio**

The Radius-to-Width (R/W) ratio, an important indicator of meander bend curvature and potential channel instability, was assessed across 13 representative bends in five zones of the river. Consistently, all measured bends maintained R/W ratios above the critical threshold of 2, suggesting that the river's curvature remained within a stable morphological regime throughout the study period (Rashid, 2020; Momin, Biswas and Tamang, 2022). Boxplot analysis confirmed that median values were moderately high, while a line plot of mean R/W values with standard error bars revealed a gradual increase between 1987 and 2023. This trend suggests a potential reduction in bend curvature and a possible shift toward channel widening or planform relaxation. The absence of $R/W < 2$ across all observation years further indicates a lack of highly unstable, tight meander formations. These findings align with broader observations of channel pattern stability in large alluvial rivers with regulated hydrologic regimes (Gleeson, 2011; Biswas *et al.*, 2021), reinforcing the interpretation of a relatively stable morphological trajectory for the Shire River over the past five decades.

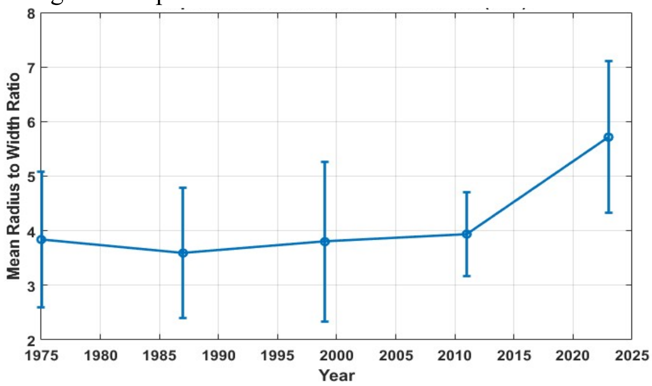

Figure 7. Channel radius to with ratio

4.5 Erosion and accretion

An analysis of sediment dynamics along the River over four successive periods (1987–1975, 1999–1987, 2011–1999, and 2023–2011) reveals a significant transition from net sediment loss to sustained sediment accumulation. Erosion rates increased from approximately 287 m² to nearly 2,987 m², while accretion rose more sharply from 106 m² to about 5,765 m², indicating a progressively dominant depositional regime. Net sediment change shifted from a negative balance in the earliest interval (–181.55 m²) to a substantial net gain of 2,778.11 m² by 2023–2011. This trend was confirmed through linear regression, yielding a strong model fit ($R^2 = 0.90$), with the equation $y = 1148.56x - 1377.50$, indicating a consistent rise in net sediment accumulation over time. These observations align with findings from similar riverine environments experiencing intensified climatic and land use impacts (Sarker *et al.*, 2014; Ibitoye, 2021).

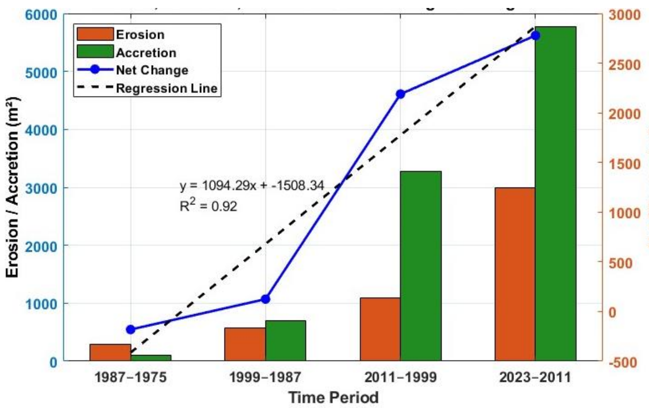

Figure 8. Erosion and accretion

5. Discussion and Conclusion

The spatiotemporal analysis of the Shire River's fluvial geomorphology from 1975 to 2023 reveals complex, yet identifiable, patterns in river morphodynamics. The findings indicate a progressive intensification in lateral channel migration, substantial channel widening, increasing sediment accretion, and fluctuating planform characteristics, such as sinuosity and meander curvature. Centerline migration analysis revealed a marked increase in lateral movement over time. The most pronounced net shift occurred during the 2011–2023 interval, with several cross sections such as SR57–SL57 and SR39–SL39 exhibiting annual migration rates exceeding 4 meters per year, accompanied by R^2 values greater than 0.90. These patterns indicate robust directional trends and are consistent with existing literature on tropical meandering rivers, which respond dynamically to climatic variability, sediment supply alterations, and hydrological disturbances (Baki and Gan, 2012; Arnaud *et al.*, 2015). Additionally, channel width expanded significantly from a mean of 4.75 meters during the 1987–1975 period to 83.64 meters in 2023–2011. This change was statistically significant, as confirmed by a repeated measures ANOVA ($p < 0.001$). Such pronounced widening, particularly after 1999, is likely attributed to flood-induced channel enlargement and declining riparian resistance due to vegetation loss or bank destabilization, as reported in similar tropical river systems (Rashid, 2020).

The sinuosity index, though variable across zones, did not exhibit statistically significant changes over the 48-year study period (ANOVA, $p = 0.223$). Nevertheless, visual trends revealed a temporary decline in sinuosity in 2011, which may be linked to channel straightening events triggered by severe flooding or anthropogenic modifications such as levee construction and embankment reinforcement (Parnell-Turner *et al.*, 2014; GoM, 2015). Notably, zones exhibiting increasing sinuosity such as Zones 3 and 5 may be undergoing meander amplification, posing increased risks of bank erosion and floodplain encroachment. In contrast, the analysis of the Radius-to-Width (R/W) ratio showed consistent values above the threshold of 2.0, indicating the presence of stable, mature meander forms and the absence of tightly curved, high-energy bends (Rashid, 2020; Roshni, Himayoun and Azim, 2021). Sediment dynamics further underscore the evolving nature of the river system. A notable transition from net sediment loss in 1987–1975 (−181.55 m^2) to significant net gain by 2023–2011 (+2778.11 m^2) was observed. This trend is strongly supported by a linear regression model with an R^2 of 0.90, indicating a persistent increase in sediment deposition over time. Contributing factors may include reduced flow velocities during low-flow seasons, sediment trapping by floodplain vegetation, upstream land use changes such as deforestation and agriculture, and altered hydrological regimes due to water abstraction or dam construction (Baki and Gan, 2012; Dewan *et al.*, 2017; Biswas, Pal and Pani, 2019).

Together, these geomorphological transformations highlight a growing vulnerability of the river corridor, especially under the pressures of climate change and increasing population density. The combined effects of channel widening, elevated sedimentation, and intensified lateral migration threaten agricultural lands, infrastructure, and human settlements. Moreover, spatial variability in sinuosity and migration rates complicates flood risk prediction and mitigation.

Conclusion

This study provides a comprehensive spatiotemporal assessment of the Shire River's fluvial geomorphological evolution from 1975 to 2023, highlighting the significant transformations occurring across key morphodynamic parameters. The results demonstrate a clear intensification of lateral channel migration, substantial widening of the river channel, a progressive increase in sediment accretion, and spatial variability in planform characteristics such as sinuosity and meander curvature. Centerline migration and channel width analyses confirm that the Shire River is undergoing accelerated morphological changes, particularly after 1999, likely in response to heightened hydrometeorological variability, flood events, and anthropogenic disturbances such as land use changes and riverbank modifications. The sediment budget trends reinforce this narrative, revealing a notable shift from net erosion to substantial net accretion in recent decades, with regression analysis indicating a strong temporal trend in sediment gain. Although sinuosity changes were not statistically significant, the presence of localized increases and decreases suggests dynamic adjustments in channel planform that may reflect underlying hydrological or structural controls.

The consistent Radius-to-Width (R/W) ratios observed across meander bends further imply morphological stability in curvature, supporting the notion of a mature, albeit actively adjusting, river system. Collectively, these findings underscore the complex interplay between natural geomorphic processes and human influences in shaping the current and future behaviour of the Shire River.

6. Recommendations

Given the observed geomorphic dynamics and their potential impacts, several management recommendations emerge. First, establishing a comprehensive, continuous monitoring program integrating remote sensing, field surveys, and GIS-based mapping is vital for tracking channel migration, width changes, and sediment dynamics. Advances in satellite imagery and UAV technology can facilitate near real-time assessment of river behaviour, enabling adaptive management responses (Dewan *et al.*, 2017). Second, flood risk zoning should incorporate zones exhibiting rapid lateral migration and significant sediment accretion to inform land-use planning, infrastructure development, and community relocation strategies. Enforcing setback distances and restricting developments in vulnerable riparian zones can mitigate erosion and flood damage risks (Sarker *et al.*, 2014). Nature-based solutions such as riparian reforestation and floodplain vegetation restoration offer sustainable means to stabilize banks, trap sediments, and enhance ecological resilience. These interventions have been successfully applied in other alluvial river systems to reduce erosion while maintaining habitat diversity (Roshni, Himayoun and Azim, 2021; Momin, Biswas and Tamang, 2022). Furthermore, sediment management should be explicitly integrated into watershed planning to identify areas prone to excessive erosion or deposition and to guide dredging or reinforcement works where necessary. Localized hydrological and sediment transport modelling is recommended to refine predictions of channel behaviour and optimize intervention designs, especially in zones exhibiting complex or non-linear migration patterns (Rashid, 2020). Finally, fostering collaborative governance involving local communities, government agencies, and scientists is essential to develop context-sensitive management strategies that balance socioeconomic needs with ecological sustainability. Community engagement through participatory mapping, awareness campaigns, and capacity-building initiatives can strengthen adaptive management and enhance resilience to climatic and anthropogenic pressures.

Limitations: One of the primary limitations of this study lies in the spatial resolution of the satellite imagery used for channel delineation and morphometric analysis. Medium-resolution datasets, while sufficient for broader geomorphic trends, may not accurately capture small-scale features such as minor bank shifts or subtle sediment deposition zones.

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