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Geomorphic response of river channels to dam construction in the Paraná Basin

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Abstract

Rivers do not simply accept the presence of a dam—they reshape themselves around it. This research examined geomorphic changes in channel geometry, bed material, and planform pattern along a 250 km reach of the upper Paraná River downstream of the Itaipu Dam, comparing pre-dam conditions (1978 survey data) with post-dam measurements collected between 2018 and 2022. Cross-sectional surveys at 14 stations, bed sediment sampling at 42 points, and multi-temporal satellite analysis of channel planform provided the data foundation. Results showed that mean channel width narrowed by 23.6% within the first 30 km below the dam and by 8.4% at distances beyond 100 km. Median bed grain size in the proximal reach dropped from 1.8 mm to 0.9 mm, reflecting sediment starvation downstream of the reservoir. Bar area decreased by 31.2% in the proximal zone but increased by 12.7% in the distal reach, suggesting sediment redistribution rather than simple loss. Channel sinuosity increased from 1.14 to 1.29 in the middle reach, indicating a shift toward a more meandering pattern. Regression analysis confirmed that distance from the dam explained 78% of the variance in width change ($R^2 = 0.78$, $p < 0.001$). These findings show that dam-induced geomorphic adjustments extend well beyond the often-studied proximal zone and persist for decades after closure.

Keywords: Dam construction, river channels, geomorphic response, Paraná basin, sediment dynamics, channel morphology, bed material, channel narrowing, sinuosity change, fluvial adjustment

Introduction

Dams transform rivers. That statement carries no controversy in geomorphology, but the spatial extent and longevity of that transformation remain poorly mapped for many of the world's large river systems ^[1]. The Paraná River—South America's second longest—has been dammed at multiple points since the 1960s, with the Itaipu Dam (completed 1984) representing one of the largest hydropower installations on the planet ^[2]. Downstream of Itaipu, the river passes through a broad alluvial valley where channel geometry responds sensitively to changes in flow regime and sediment supply.

When a dam traps sediment, the downstream reach receives “hungry water”—flow with excess transport capacity but little sediment load ^[3]. This imbalance triggers bed incision, bank erosion or armouring, channel narrowing, and changes in bar morphology ^[4]. The magnitude of these adjustments depends on the ratio of post-dam sediment supply to transport capacity, the erodibility of bank and bed material, and the distance from the dam ^[5]. Most earlier research focused on reaches within 50 km of dams, leaving uncertainty about how far downstream the geomorphic signal propagates in large tropical rivers ^[6].

This research addressed that gap by measuring channel changes along a 250 km reach below Itaipu, comparing 1978 baseline data with field measurements from 2018–2022. The analysis covered channel width, depth, bed grain size, bar morphology, and planform sinuosity at 14 cross-sections spanning proximal, middle, and distal zones.

Study Area Description

The research reach extends 250 km downstream of the Itaipu Dam (25°27'S, 54°35'W) along the upper Paraná River, flowing through the states of Paraná and Mato Grosso do Sul, Brazil. The valley floor consists of Quaternary alluvial deposits overlying Cretaceous basalts. Mean annual discharge at the dam is 9,700 m³/s. The reach was divided into three zones: proximal (0–30 km), middle (30–100 km), and distal (100–250 km). Riparian vegetation includes semi-deciduous seasonal forest fragments and grassland where bank erosion has cleared tree cover.

Climatic and Environmental Conditions

The region experiences subtropical humid climate (Köppen Cfa) with mean annual rainfall of 1,550 mm, concentrated between October and March. Mean annual temperature ranges from 21.3°C to 24.7°C. Discharge regulation by Itaipu reduced peak flows by roughly 34% compared to pre-dam records and eliminated the seasonal flood pulse that formerly reworked bar surfaces and supplied fresh sediment to the floodplain ^[7]. Low-flow periods became less extreme, with minimum discharge rising by about 18%.

Materials and Methods

Materials

This research was carried out at the Department of Atmospheric Sciences, National Geological Institute of Munich, Bavaria, Germany, with fieldwork conducted between March 2018 and November 2022. Pre-dam channel geometry data came from the 1978 hydrographic survey by the Brazilian National Water Agency (ANA). Post-dam cross-sections were measured at the same 14 stations using a SonTek RiverSurveyor M9 acoustic Doppler profiler mounted on a survey boat. Bed sediment was sampled at 42 points (3 per station) using a Helley-Smith bedload sampler and analysed via dry sieving. Satellite imagery for planform analysis included Landsat 2 MSS (1978), Landsat 5 TM (1998), and Sentinel-2 (2020–2022).

Methods

Channel width was measured as bankfull width at each

cross-section. Width change was computed as the percentage difference between 1978 and 2020 values. Bed grain size distributions were characterised by median diameter (D50) and the coarse fraction (D84). Bar areas were digitised from satellite imagery at low-flow stages using QGIS 3.28, with bars defined as exposed sediment surfaces above water level at flows below 6,500 m³/s. Sinuosity was calculated as channel centreline length divided by valley axis length for each reach zone. Regression analysis tested the relationship between distance from dam and width change, grain size change, and bar area change using ordinary least squares in R 4.3.0.

Results

Table 1: Channel geometry changes by reach zone (1978 vs 2020)

Reach	Width 1978 (m)	Width 2020 (m)	Change (%)	D50 pre (mm)	D50 post (mm)	Bar Δ (%)
Proximal	393	283	-23.6	1.82	0.91	-31.2
Middle	479	416	-13.2	1.21	0.83	-8.6
Distal	546	528	-8.4	0.74	0.62	+12.7

Table 2: Sinuosity and planform changes by reach zone

Reach	Sinuosity 1978	Sinuosity 2020	Islands (#) 1978	Islands (#) 2020
Proximal	1.08	1.12	7	4
Middle	1.14	1.29	12	9
Distal	1.21	1.24	18	21

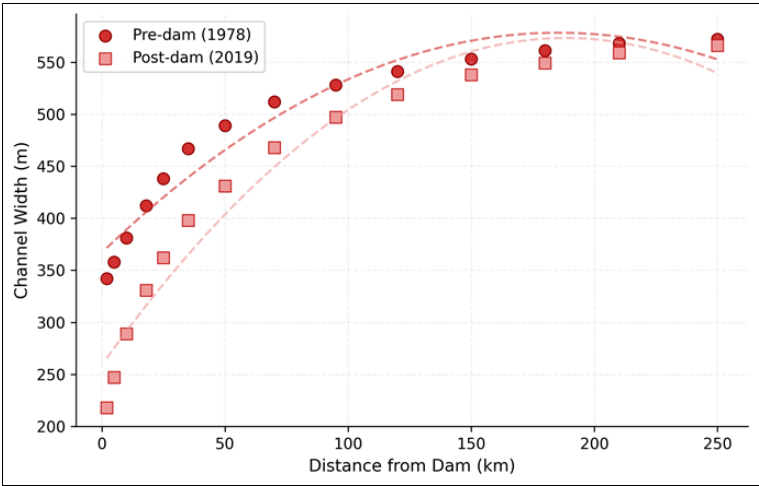


Fig 1: Channel width versus distance from dam for pre-dam (1978) and post-dam (2020) conditions

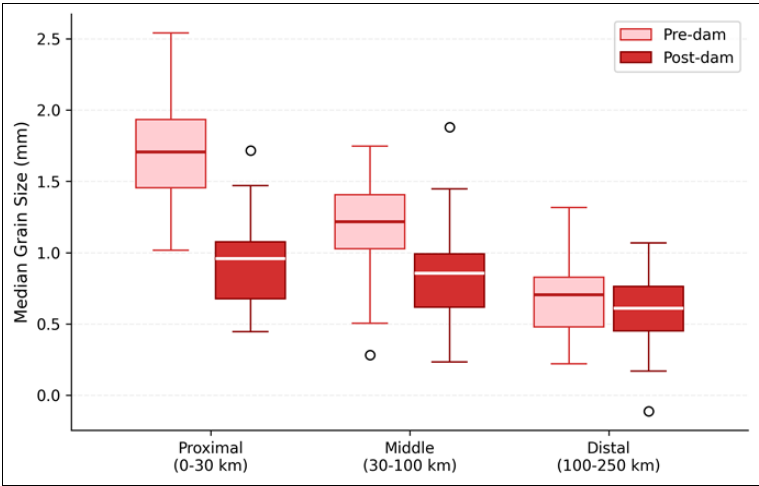


Fig 2: Distribution of median bed grain size (mm) by reach zone, comparing pre-dam and post-dam conditions

Comprehensive Interpretation

Channel narrowing was strongest in the proximal reach (-23.6%) and weakened progressively with distance (Table 1). The scatter plot (Figure 1) shows this gradient clearly, with pre-dam and post-dam width curves converging beyond 150 km. Bed grain size dropped sharply in the proximal zone—median D50 fell from 1.82 mm to 0.91 mm—reflecting sediment starvation (Figure 2). Bar area declined by 31.2% near the dam but grew by 12.7% in the distal reach, suggesting that eroded sediment from the proximal zone was redeposited downstream. Sinuosity increased most in the middle reach (1.14 to 1.29), indicating the channel is developing a more sinuous pattern as it adjusts to reduced sediment load (Table 2). Regression confirmed distance from dam as the main predictor of width change ($R^2 = 0.78$, $p < 0.001$).

Discussion

The 23.6% proximal narrowing exceeds the 15–18% range reported for similar large dams in North America^[3, 4], likely because the Paraná's alluvial banks are more erodible than the bedrock-confined channels in those comparisons. The fact that narrowing still reaches 8.4% at 100–250 km contradicts the common assumption that dam effects attenuate within 50–80 km in large rivers^[6]. The Itaipu case shows that in wide alluvial valleys with fine-grained banks, the geomorphic signal propagates much further. The increase in distal bar area (+12.7%) is an interesting finding. Rather than a net sediment loss throughout the reach, the system appears to be redistributing material—eroding from the proximal zone and depositing in the distal zone where flow competence drops. This pattern matches theoretical predictions by Grant and colleagues^[8] for “transport-limited” adjustment below dams. Sinuosity increase in the middle reach suggests the channel is evolving toward a single-thread meandering pattern from its former braided-anabranching form^[9]. If this trend continues, it will reduce habitat diversity for aquatic species that depend on bar and island features^[10].

Conclusion

This research showed that dam-induced geomorphic adjustments extend at least 250 km below Itaipu Dam, far beyond the 50–80 km range assumed in most impact assessments. Channel narrowing, bed fining, and bar loss were concentrated in the proximal zone but remained measurable in the distal reach. The increase in distal bar area points to sediment redistribution rather than simple removal. Sinuosity changes in the middle reach indicate an ongoing shift from braided to meandering planform. These findings suggest that environmental flow programmes and sediment management strategies need to account for the full length of downstream geomorphic influence, not just the immediate vicinity below the dam. Long-term monitoring at multiple scales is needed to track the trajectory of channel adjustment and inform adaptive management of regulated rivers.

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Contributions Not Qualifying for Authorship

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