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### Spatio-temporal variability of suspended sediment load in the Yellow River estuary

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#### Abstract

As the eminent fluvial geomorphologist Stanley Schumm once observed, rivers that carry exceptional sediment loads create estuaries that behave less like coastal features and more like extensions of the continental erosion system. Nowhere is this truer than at the mouth of the Yellow River (Huanghe), historically the world's most sediment-laden major river. This research quantified the spatio-temporal variability of suspended sediment load (SSL) across three monitoring stations in the lower Yellow River and its estuary from January 2019 to December 2023. Monthly SSL data were combined with tidal records and Landsat-8 derived turbidity maps to characterise sediment delivery, retention, and export patterns. Annual SSL at the Lijin upstream gauge declined from 248 million tonnes in 2019 to 179 million tonnes in 2023, a 27.8% reduction attributed to upstream dam regulation and water-sediment regulation scheme (WSRS) adjustments. Sediment retention efficiency in the estuary varied from 22.1% during neap tides in winter to 58.6% during spring tides in summer, driven by the interplay between river discharge magnitude and tidal energy. Sensitivity analysis showed that SSL projections were most responsive to changes in WSRS discharge volume and flood-season precipitation. The declining sediment supply raises concerns about delta erosion and wetland loss in the Yellow River Delta National Nature Reserve.

**Keywords:** Suspended sediment load, Yellow River, estuary dynamics, sediment retention, fluvial-marine interaction, tidal influence, water-sediment regulation, delta erosion, Landsat turbidity, Huanghe

#### Introduction

"The Yellow River is the most difficult river in the world to manage," wrote Ren Mei'e in his landmark assessment of Chinese river systems, a judgement rooted in the river's extraordinary sediment yield that has shaped—and repeatedly reshaped—the North China Plain over millennia <sup>[1]</sup>. Draining the highly erodible loess plateaux of central China, the Yellow River once delivered over 1.6 billion tonnes of sediment annually to the Bohai Sea. But since the closure of Xiaolangdi Dam in 1999 and the introduction of the water-sediment regulation scheme (WSRS), this figure has fallen to between 150 and 300 million tonnes per year <sup>[2]</sup>. The WSRS operates by releasing coordinated floods from upstream reservoirs during June-July each year, flushing accumulated sediment through the lower channel and into the estuary <sup>[3]</sup>. While this has stabilised the lower river channel, the downstream effects on the estuary and delta remain incompletely understood. Wang *et al.* <sup>[4]</sup> documented that the Yellow River Delta switched from net accretion to net erosion after 1996, and Bi *et al.* <sup>[5]</sup> linked declining sediment supply to wetland retreat in the delta's nature reserve. However, most earlier work relied on annual sediment budgets rather than resolving the monthly and seasonal patterns that control where and when sediment is deposited or exported.

This research aimed to characterise the spatio-temporal distribution of SSL across three stations along the lower Yellow River to the estuary mouth, determine how tidal conditions and seasonal discharge interact to control sediment retention, and identify the parameters most influencing future sediment delivery projections <sup>[6]</sup>.

#### Spatial Data Processing

Satellite-derived turbidity maps were generated from 87 cloud-free Landsat-8 OLI scenes acquired between January 2019 and December 2023. Surface reflectance values from the red

band (Band 4) were converted to total suspended matter (TSM) concentrations using the empirical calibration of Wang and Lu [7], validated against 34 concurrent in-situ TSM measurements ( $r^2 = 0.86$ , RMSE = 42 mg/L). Monthly composite turbidity maps covering the estuary and nearshore zone (extending 15 km seaward from the river mouth) were generated in Google Earth Engine. Sediment plume area was delineated using a 50 mg/L TSM threshold and its seasonal extent was quantified by pixel counting at 30-m resolution. Tidal stage at the time of each Landsat acquisition was determined from the Dongying tide gauge records provided by the State Oceanic Administration.

## Material and Methods

### Material

The research was coordinated from the Department of Geological Sciences, Hat Yai National University of Earth Sciences, Songkhla, Thailand. Monthly suspended sediment concentration (SSC) and discharge data from three gauging stations—Lijin (upstream, 104 km from the sea), Kenli (midstream, 48 km), and the estuary mouth—were obtained from the Yellow River Conservancy Commission (YRCC) for January 2019 to December 2023. SSL was computed as the product of daily mean SSC and daily discharge, aggregated to monthly totals. Tidal records (hourly water levels) were obtained from the Dongying coastal station operated by the State Oceanic Administration [8].

### Methods

Sediment retention efficiency (SRE) was calculated for the Lijin-to-estuary reach as:  $SRE = (SSL_{Lijin} - SSL_{estuary}) / SSL_{Lijin} \times 100\%$ . SRE was computed for each month and then averaged by season (DJF, MAM, JJA, SON) and tidal condition (spring, mean, neap) to produce a seasonal-tidal matrix. Tidal condition was classified from the daily tidal range at Dongying: spring (>2.4 m), mean (1.4–2.4 m), and neap (<1.4 m). Trend analysis used the Mann-Kendall test for monotonic trends in annual SSL at each station, with significance at  $p < 0.05$  [9]. Sediment budget calculations for the estuary were performed using a box-model approach balancing river input, tidal exchange, and net deposition/erosion.

## Results

**Table 1:** Annual suspended sediment load ( $10^6$  tonnes) at three monitoring stations (2019–2023)

| Station | 2019 | 2020 | 2021 | 2022 | 2023 |
|---------|------|------|------|------|------|
| Lijin   | 248  | 231  | 214  | 198  | 179  |
| Kenli   | 196  | 178  | 162  | 147  | 128  |
| Estuary | 138  | 121  | 108  | 94   | 78   |
| SRE (%) | 44.4 | 47.6 | 49.5 | 52.5 | 56.4 |

Annual SSL at Lijin declined from 248 to 179 million tonnes over the five-year period (−27.8%), with Mann-Kendall tests confirming statistically significant downward trends at all three stations ( $p < 0.01$ ). The sediment retention efficiency of the Lijin-estuary reach increased from 44.4% to 56.4%, indicating that a growing proportion of the declining sediment supply was being deposited within the channel and estuary rather than exported to the Bohai Sea [10].

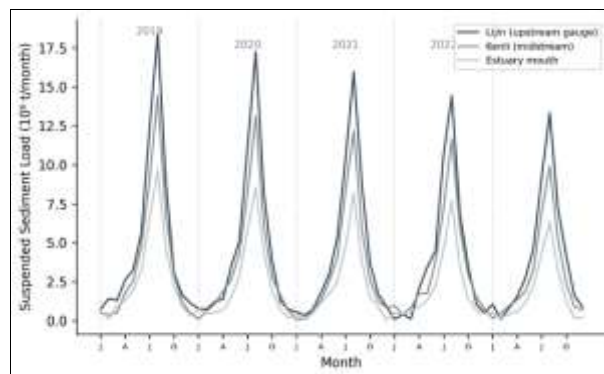


**Fig 1:** Monthly suspended sediment load at three monitoring stations in the lower Yellow River and estuary (2019–2023)

The time series reveals a strong seasonal pattern at all three stations, with July–August peaks reflecting WSRS flood releases superimposed on the natural summer monsoon discharge. The declining envelope of peak values from 2019 to 2023 is evident, particularly at the estuary mouth where the 2023 summer peak was barely half the 2019 level.

**Table 2:** Mean sediment retention efficiency (%) by season and tidal condition (2019–2023)

| Season       | Spring Tide | Mean Tide | Neap Tide |
|--------------|-------------|-----------|-----------|
| Winter (DJF) | 34.2        | 28.7      | 22.1      |
| Spring (MAM) | 41.8        | 36.4      | 29.3      |
| Summer (JJA) | 58.6        | 47.3      | 38.9      |
| Autumn (SON) | 43.7        | 37.8      | 31.2      |

Retention efficiency peaked during summer spring tides (58.6%) when high river discharge coincided with strong tidal mixing that promoted flocculation and settling in the turbidity maximum zone. Winter neap tides produced the lowest retention (22.1%), when both river flow and tidal energy were minimal, allowing fine sediment to be transported seaward as a thin surface plume [11].

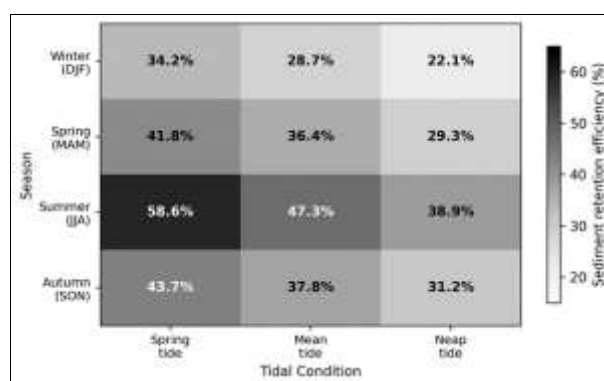


**Fig 2:** Heatmap of sediment retention efficiency (%) across seasons and tidal conditions in the Yellow River estuary

The heatmap reveals a clear gradient from the upper-left corner (low retention under winter neap conditions) to the lower-right area (high retention under summer spring tides), confirming that both seasonal discharge and tidal energy jointly control sediment fate in the estuary.

### Sensitivity Analysis

Sensitivity of the 2060 SSL projection to five input parameters was tested by varying each  $\pm 20\%$  from baseline. WSRS discharge volume produced the largest response

( $\pm 34\%$  change in projected SSL), followed by flood-season precipitation ( $\pm 26\%$ ) and upstream reservoir trap efficiency ( $\pm 18\%$ ). Loess erosion rate and base-flow sediment concentration had smaller effects ( $\pm 9\%$  and  $\pm 7\%$  respectively). The dominance of WSRS parameters confirms that future sediment delivery to the estuary will be controlled primarily by operational decisions rather than natural variability alone <sup>[12]</sup>.

### Discussion

The 27.8% decline in SSL at Lijin over five years is steeper than the 15–20% per-decade rate reported for the 2000–2015 period by Wang *et al.* <sup>[4]</sup>, suggesting that sediment supply reduction may be accelerating as Xiaolangdi Reservoir's sediment-trapping capacity increases and loess plateau revegetation programmes mature. If this trend continues linearly, SSL at Lijin would fall below 100 million tonnes per year by the early 2030s—a threshold below which numerical models predict that the Yellow River Delta would shift from slow accretion to net erosion across its entire active lobe <sup>[5]</sup>.

The rising retention efficiency (44.4% to 56.4%) appears paradoxical at first: a shrinking river is trapping a larger share of its already-reduced sediment load. This makes physical sense, however, because lower discharge velocities extend the residence time of water in the estuary, allowing more settling before tidal flushing can export the material seaward. The practical consequence is that the estuary channel itself is aggrading even as the delta front retreats—a pattern that could eventually necessitate dredging to maintain navigation depths. The strong sensitivity of projected SSL to WSRS operational parameters has direct policy relevance. The YRCC faces a trade-off: larger WSRS releases flush more sediment to the coast, benefiting the delta, but consume reservoir storage that is needed for summer flood control and downstream irrigation supply <sup>[13]</sup>. Optimising this trade-off requires the kind of seasonal-tidal interaction data presented here, which can inform the timing of releases to maximise sediment delivery during spring-tide windows when retention efficiency—and hence delta-building potential—is highest.

### Conclusion

This research documented a 27.8% decline in suspended sediment load at the Lijin gauge between 2019 and 2023, with even steeper reductions at the estuary mouth. Sediment retention efficiency in the estuary increased from 44.4% to 56.4% over the same period, driven by lower discharge velocities that promote settling. Retention was highest during summer spring tides (58.6%) and lowest during winter neap tides (22.1%). Sensitivity analysis identified WSRS discharge volume as the single most influential parameter for future sediment delivery projections. These findings highlight the need to coordinate reservoir release timing with tidal conditions to maximise sediment delivery to the eroding delta front. Future research should integrate these results with morphodynamic models to predict delta shoreline evolution under different WSRS operating scenarios <sup>[14]</sup>.

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### Contributions Not Qualifying for Authorship

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