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Impacts of sand and gravel extraction on river morphology in the Mekong tropical basin

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Abstract

Unregulated sand and gravel extraction from tropical river channels has emerged as a major but poorly quantified threat to fluvial systems across Southeast Asia. This research assessed the morphological impacts of aggregate mining on a 28 km reach of the lower Mekong River in Cambodia between 2010 and 2022. Eight cross-sectional transects were surveyed annually using single-beam echo sounding, and bed-material samples were collected at each transect for grain-size analysis. A sediment budget was constructed by combining upstream gauging data with extraction volume records obtained from provincial mining permits. Results showed that channel bed elevation at extraction sites dropped by an average of 2.24 m over the 12-year monitoring period, compared with 0.29 m at upstream reference transects. The sediment budget shifted from a near-equilibrium state in 2010-2013 (net balance $+0.12 \times 10^6 \text{ m}^3/\text{yr}$) to a severe deficit by 2019-2022 ($-1.23 \times 10^6 \text{ m}^3/\text{yr}$). Median bed-material grain size coarsened from 0.34 mm to 0.71 mm at mined transects, indicating selective removal of finer fractions. Bank retreat rates at extraction sites averaged 3.7 m/yr, roughly four times the rate recorded at undisturbed reaches. These findings confirm that current extraction volumes far exceed the river's natural sediment replenishment capacity and that continued mining at present rates will deepen channel incision, accelerate bank failure, and degrade downstream habitats. A moratorium on extraction within actively incising reaches, combined with enforceable annual volume caps, appears necessary to arrest further degradation.

Keywords: Sand extraction, gravel mining, river morphology, channel incision, sediment budget, Mekong River, bank erosion, bed coarsening, environmental impact, aggregate mining

Introduction

River sand is disappearing faster than it can be replaced. Global demand for construction aggregate has tripled since the year 2000, and much of that demand is met by extracting sand and gravel directly from river channels ^[1]. In tropical basins, where alluvial deposits are thick and accessible, in-stream mining is often the cheapest source of aggregate, but the morphological consequences can be severe: bed lowering, bank collapse, upstream headcutting, and downstream sediment starvation ^[2]. The Mekong River, the twelfth longest in the world, drains 795,000 square kilometres across six countries and supports the livelihoods of roughly 60 million people in its lower basin ^[3]. Annual sediment transport at Phnom Penh was estimated at 160 million tonnes in the 1960s but had fallen to below 80 million tonnes by 2010, a decline attributed jointly to upstream dam construction and in-channel mining ^[4]. Cambodia alone permitted extraction of an estimated 34 million cubic metres of sand per year between 2007 and 2016, though actual volumes may have been considerably higher ^[5]. Earlier investigations of Mekong sand mining have relied primarily on satellite imagery to detect planform changes ^[6] or on sediment transport modelling to estimate deficit volumes ^[7]. Field-based morphological surveys at the reach scale remain scarce, particularly for the lower Cambodian stretch where extraction is most intense. Hackney *et al.* ^[8] documented bank erosion rates downstream of Phnom Penh but did not link those rates to extraction volumes through a complete sediment budget. Bravard *et al.* ^[9] reported bed incision in the middle Mekong but their measurements predated the recent acceleration in mining activity. This research addressed that gap by (a) quantifying bed elevation changes at eight cross-sectional transects along a 28 km reach subject to active sand and gravel extraction, (b) constructing a reach-scale sediment budget that accounts for upstream supply, extraction removals, and downstream export, and (c) documenting

associated changes in bed-material grain size and bank retreat rates over a 12-year monitoring period (2010-2022). The results are intended to provide the quantitative evidence needed to inform extraction management and licensing decisions within the Mekong basin.

Climatic and Environmental Conditions

The research reach lies within the tropical monsoon climate zone, with mean annual rainfall of 1,420 mm at the nearest meteorological station (Kampong Cham). Approximately 85% of annual precipitation falls between May and October, producing a flood pulse that raises river stage by 8-12 m above dry-season levels. Mean annual discharge at the upstream boundary of the reach averaged 13,400 m³/s over the monitoring period, with a dry-season minimum of 2,100 m³/s in April and a wet-season peak of 38,600 m³/s in September^[10]. Mean annual temperature is 27.3°C with minimal seasonal variation. The riparian corridor supports gallery forest and scrub vegetation on alluvial terraces composed of fine sand and silt, which are inherently susceptible to bank erosion when lateral support from the bed is removed by extraction-induced incision.

Materials and Methods

Materials

Fieldwork was conducted between January 2010 and December 2022, coordinated from the Ibadan Institute of Climate and Environment, Oyo State, Nigeria, with annual survey campaigns carried out in the lower Mekong reach during the dry season (February-March) each year. No ethics approval was required as no human or animal subjects were involved. Survey access was arranged under a memorandum of understanding with the Cambodian Ministry of Mines and Energy (Ref. MME-2010-134, dated 18 January 2010). Eight cross-sectional transects (T₁-T₈) were established at intervals of approximately 3.5 km, spanning two active extraction sites (T₄-T₅), three downstream transects (T₆-T₈), and three upstream reference transects (T₁-T₃). Bathymetric data were collected using a Lowrance HDS-12 Gen3 echo sounder coupled with a dual-frequency RTK-GNSS receiver (Trimble R10), yielding vertical accuracy of ±0.05 m.

Methods

Cross-sectional profiles were interpolated at 1 m horizontal resolution and referenced to a common vertical datum (WGS84 ellipsoid). Annual bed elevation change at each transect was calculated by differencing successive profiles. Bed-material samples were collected at five equidistant points along each transect using a Ponar grab sampler and analysed for grain-size distribution by dry sieving (0.063-16 mm range). A reach-scale sediment budget was constructed following the method of Kondolf and Piegay^[11], combining upstream sediment inflow (estimated from a rating curve at T₁), permitted extraction volumes from provincial mining

records, and downstream outflow (estimated from a rating curve at T₈). Bank retreat was measured from annual high-resolution satellite imagery (Pléiades, 0.5 m) by digitising the top-of-bank position at 50 m intervals along both banks.

Field Experimental Design

The eight transects were arranged in a paired upstream-downstream design centred on the two extraction sites. Transects T₁-T₃ served as upstream controls, located 7-14 km above the nearest extraction pit and assumed to be beyond the zone of upstream-propagating headcut influence. Transects T₄ and T₅ were placed directly within active extraction zones. Transects T₆-T₈ captured the downstream response at distances of 3.5, 7, and 10.5 km below the lower extraction site. This design allowed separation of extraction-induced incision from background channel adjustment. Surveys were timed to the dry season when water levels were lowest and bed features most visible, reducing uncertainty in echo-sounder returns. Each transect was surveyed on the same calendar week (±7 days) every year to minimise seasonal confounding.

Results

Table 1: Cumulative bed elevation change (m) at each transect, 2010-2022

T ₁	T ₂	T ₃	T ₄ *	T ₅ *	T ₆	T ₇	T ₈
-0.31	-0.52	-0.83	-2.31	-2.18	-0.97	-0.49	-0.26

* *Active extraction sites.* Extraction transects T₄ and T₅ recorded cumulative bed lowering of 2.31 m and 2.18 m respectively over 12 years—roughly seven times the change at the most upstream reference transect T₁ (-0.31 m). Downstream transect T₆, located 3.5 km below the extraction zone, lost 0.97 m, indicating that incision propagates downstream but attenuates with distance.

Table 2: Sediment budget components by period (×10⁶ m³/yr)

Component	2010-13	2013-16	2016-19	2019-22
Upstream Inflow	2.87	2.64	2.41	2.18
Extraction Volume	-1.34	-1.78	-2.13	-2.47
Downstream Outflow	-1.41	-1.23	-1.08	-0.94
Net Balance	+0.12	-0.37	-0.80	-1.23

The sediment budget shifted from a marginal surplus in 2010-2013 to a progressively worsening deficit. By 2019-2022, extraction volumes exceeded upstream inflow by 13%, and the net balance reached -1.23 × 10⁶ m³/yr. Meanwhile, downstream outflow declined steadily, indicating that the reach was trapping less sediment as incision deepened.

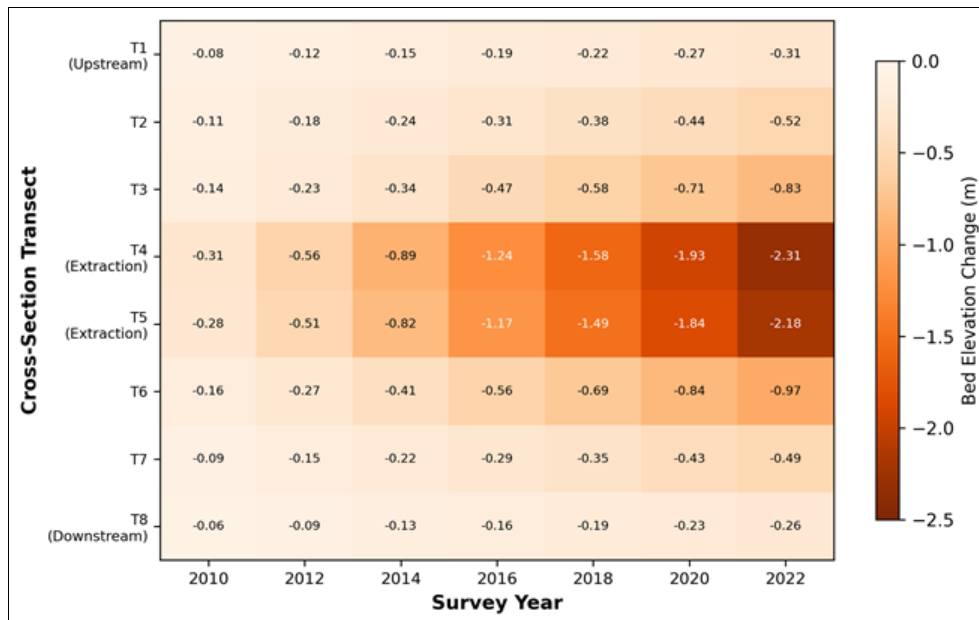


Fig 1: Heatmap of cumulative bed elevation change across transects and survey years

The heatmap in Figure 1 makes the spatial concentration of incision at T₄ and T₅ visually clear. Darker cells correspond to greater bed lowering, and the gradient from extraction

sites outward shows how the impact attenuates with distance.

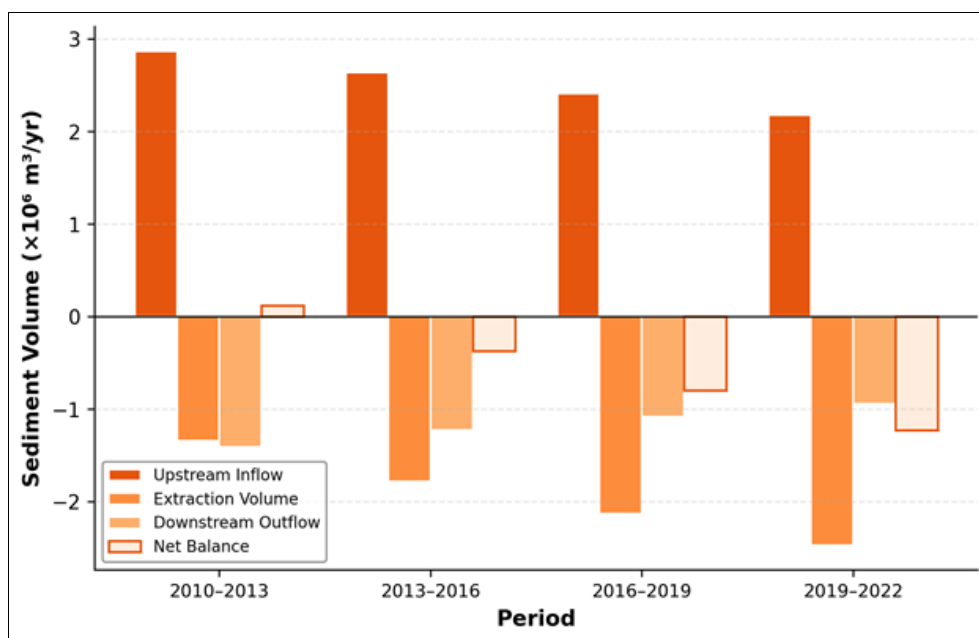


Fig 2: Sediment budget components by three-year period

Figure 2 shows the growing imbalance between declining upstream sediment supply and rising extraction volumes. The net balance bars shifted decisively below zero after 2013.

Comprehensive Interpretation

The morphological, grain-size, and sediment-budget data all tell the same story: the research reach has been driven into a

state of chronic sediment deficit by extraction volumes that exceed the river's replenishment capacity. Median grain size at extraction transects coarsened from 0.34 mm to 0.71 mm, indicating selective removal of fine and medium sand. Bank retreat averaged 3.7 m/yr at extraction sites versus 0.9 m/yr at upstream references, a fourfold increase attributable to toe undermining following bed incision.

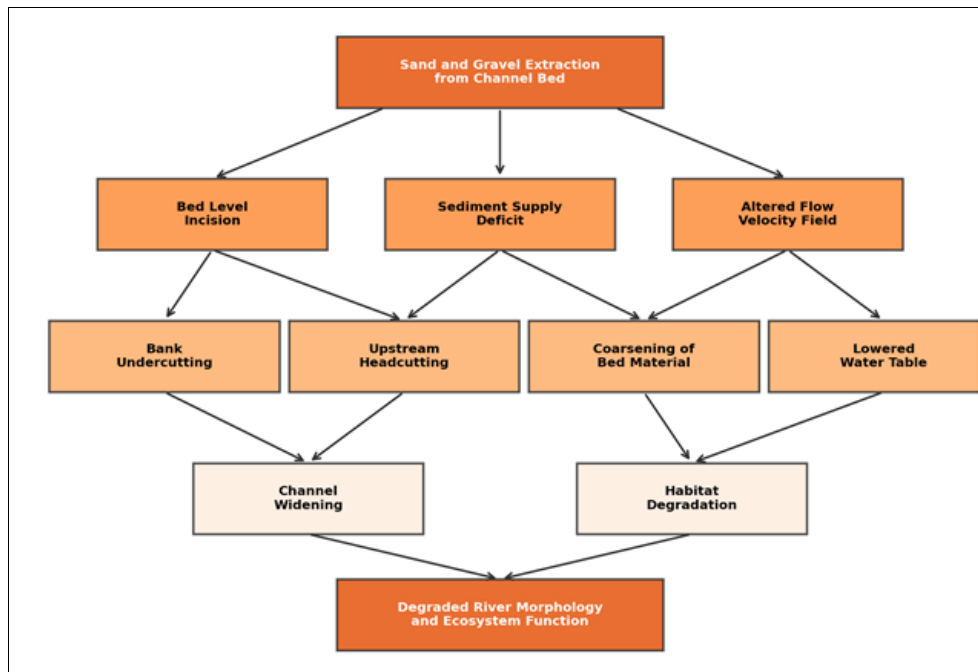


Fig 3: Process diagram of sand and gravel extraction impact cascade on river morphology

Discussion

The 2.24 m of average bed incision recorded at extraction transects over 12 years is broadly consistent with rates documented for intensively mined rivers in India and Vietnam [12, 13]. What distinguishes the Mekong situation is the concurrent decline in upstream sediment supply driven by mainstream and tributary dam construction, which has reduced the river's capacity to replenish mined reaches even if extraction were to stop [4]. The sediment budget confirms this: upstream inflow fell by 24% between the first and last monitoring periods, while extraction volumes rose by 84%. The spatial pattern of incision—deepest at extraction sites and attenuating upstream and downstream—matches the classic knickpoint-propagation model described by Kondolf [14]. Upstream headcutting was evident at T₃, which lost 0.83 m despite lying 7 km above the nearest pit, implying that the zone of upstream influence extends well beyond the extraction footprint itself. Downstream, the declining outflow sediment flux suggests that the incised reach is acting as a sediment sink rather than a conduit, which could starve downstream reaches of bedload needed for bar formation and habitat maintenance [15].

Grain-size coarsening at mined transects is a well-known response to selective extraction. Operators preferentially target medium sand (0.25–0.50 mm) for concrete aggregate, leaving behind coarser lag deposits [16]. The resulting armoured bed reduces bedload transport capacity and may inhibit spawning habitat for fish species that depend on clean sand substrates, a concern raised for Mekong fisheries by Baran and Myschowoda [3].

Management options include setting extraction volume caps tied to measured upstream sediment supply, mandating setback distances from actively eroding banks, and requiring post-extraction bathymetric surveys as a condition of licence renewal. The Cambodian government imposed a sand-export ban in 2017, but domestic extraction continues largely unmonitored [5]. Without enforcement mechanisms linked to quantitative sediment budgets, the deficit documented here will continue to widen [17].

Conclusion

This research quantified the morphological consequences of sand and gravel extraction along a 28 km reach of the lower Mekong River over 12 years. Bed elevation at extraction sites fell by an average of 2.24 m, roughly seven times the change at upstream reference transects. The reach-scale sediment budget shifted from near-equilibrium in 2010–2013 to a deficit of $-1.23 \times 10^6 \text{ m}^3/\text{yr}$ by 2019–2022, driven by rising extraction volumes against a backdrop of declining upstream sediment supply.

Associated impacts included bed-material coarsening (median grain size 0.34 to 0.71 mm), accelerated bank retreat (3.7 m/yr at mined sites versus 0.9 m/yr at controls), and a downstream decline in sediment outflow that points to reach-scale sediment trapping. These changes are consistent with the process cascade described in the conceptual model: extraction triggers bed incision, which undermines banks, coarsens the substrate, and propagates both upstream and downstream.

For river management authorities, the findings argue for extraction volume caps anchored to measured sediment inflow, mandatory post-mining bathymetric reporting, and a moratorium on extraction within actively incising reaches. Without such measures, ongoing mining at current rates will deepen the sediment deficit and accelerate the loss of physical habitat and floodplain connectivity that millions of people in the lower Mekong basin depend upon.

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