JOURNAL OF ENGINEERING, INFRASTRUCTURE AND GEOSCIENCES

Volume 2, Number 2 (2026) · October 2026
e-ISSN 3165-3324
Research Center Progresif
jeig@researchcenterprogresif.org

SEDIMENT BUDGETS AS A LICENSING INPUT FOR SUSTAINABLE RIVER SAND EXTRACTION

Aloisius Yonathan Prakoso[1*]

[1]Ministry of Investment and Downstream Industry (BKPM), Jakarta, Indonesia
*Corresponding author: aloisius@bkpm.go.id

Article History
Received: 09-09-2026
Accepted: 06-11-2026

Keywords:
sediment budget; sand mining; river channel incision; extraction licensing; aggregate resources

ABSTRACT

Sand and gravel are the second most extracted material on earth after water, yet extraction permits are almost universally issued as volume entitlements without reference to how much sediment the river in question actually supplies. This study asks whether the sediment budget — the accounting identity relating sediment inputs, storage and outputs in a river reach — can be operationalised as a licensing input, and what would be required to do so. The method combines a structured review of research published between 2017 and 2024 with a secondary synthesis of published extraction and supply quantities, and a design-oriented analysis that translates the budget identity into licensing parameters. The evidence assembled shows systematic deficit at every scale examined. Global extraction approaches fifty billion tonnes annually and is rising at roughly six per cent per year, while natural production replaces only about half of what is removed. In the lower Mekong, extraction of fifty million tonnes per year confronts a natural sand supply of 6.18 million tonnes, an eightfold deficit associated with bed lowering averaging 0.13 metres per year, and in the Cambodian reach only two of sixty observed months recorded a positive sand budget. The study concludes that volume-based permitting is not a weak form of sediment management but a different exercise, and specifies five parameters — reach definition, supply estimate, deficit tolerance, monitoring interval and an unlicensed-extraction allowance — through which a budget-referenced permit could be constructed with presently available remote-sensing methods.

ABSTRAK

Pasir dan kerikil merupakan material kedua paling banyak diekstraksi di bumi setelah air, namun izin penambangan hampir selalu diterbitkan sebagai hak atas volume tanpa merujuk pada berapa banyak sedimen yang sesungguhnya dipasok sungai bersangkutan. Penelitian ini menanyakan apakah neraca sedimen — identitas akuntansi yang menghubungkan masukan, simpanan, dan keluaran sedimen pada satu ruas sungai — dapat dioperasionalkan sebagai masukan perizinan, dan apa yang diperlukan untuk itu. Metodenya memadukan telaah terstruktur riset terbitan 2017 hingga 2024, sintesis sekunder atas angka ekstraksi dan suplai yang telah dipublikasikan, serta analisis berorientasi desain yang menerjemahkan identitas neraca menjadi parameter perizinan. Bukti yang dihimpun menunjukkan defisit sistematis pada setiap skala yang ditelaah. Ekstraksi global mendekati lima puluh miliar ton per tahun dan naik sekitar enam persen per tahun, sementara produksi alami hanya menggantikan separuh dari yang diambil. Di Mekong hilir, ekstraksi lima puluh juta ton per tahun berhadapan dengan suplai pasir alami 6,18 juta ton, defisit delapan kali lipat yang berasosiasi dengan penurunan dasar sungai rata-rata 0,13 meter per tahun, dan di ruas Kamboja hanya dua dari enam puluh bulan pengamatan mencatat neraca

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

pasir positif. Penelitian menyimpulkan bahwa perizinan berbasis volume bukanlah bentuk lemah dari pengelolaan sedimen melainkan latihan yang sama sekali berbeda, dan merinci lima parameter — definisi ruas, estimasi suplai, toleransi defisit, interval pemantauan, dan kelonggaran ekstraksi tanpa izin — yang melaluinya izin berbasis neraca dapat disusun dengan metode penginderaan jauh yang tersedia saat ini.
Kata kunci: neraca sedimen; penambangan pasir; penurunan dasar sungai; perizinan tambang; agregat

1. INTRODUCTION

Concrete requires sand. So does glass, asphalt, land reclamation and road base, which is to say that sand underlies most of what constitutes modern construction. The result is an extractive industry of extraordinary scale that attracts a small fraction of the policy attention devoted to fossil fuels or to metals, despite moving more material annually than either.

Scale alone, however, is not the analytical problem. Many materials are extracted in large quantities without provoking a governance crisis, because extraction is measured against a stock or a flow that is itself measured. What distinguishes river sand is that the quantity removed is licensed, taxed and recorded, while the quantity supplied is neither measured nor considered. A permit to extract fifty thousand cubic metres from a river reach is a statement about the operator's entitlement. It is not a statement about the river, and in the absence of any estimate of what the river delivers to that reach, it cannot be evaluated as one.

This asymmetry is the subject of the present study. Fluvial geomorphology has long possessed the conceptual apparatus needed to evaluate extraction: the sediment budget, an accounting identity relating the sediment entering a reach, the sediment leaving it, and the resulting change in storage. When outputs exceed inputs the reach loses material, the bed lowers, banks are undercut and collapse, and the effects propagate downstream to reaches where no extraction occurred. This is not contested science. What is absent is any regular translation of it into the administrative instrument that actually governs extraction, which is the licence.

The gap matters most where measurement is weakest. Recent reviews of the evidence on riverine extraction note that the rivers for which the strongest scientific evidence exists are not the rivers where extraction is most intense, which implies that the documented cases understate rather than represent the global condition. Indonesia, whose rivers supply a

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

construction sector under sustained infrastructure demand and whose sand extraction is widespread, small-scale and partly unlicensed, sits in the under-measured category.

This study therefore asks three questions. First, what does the peer-reviewed evidence published between 2017 and 2024 establish about the relationship between extraction and sediment supply, at global and basin scales? Second, what physical consequences follow from a sustained deficit, and how reliably can they be attributed and measured? Third, what would be required to convert the sediment budget from a research instrument into a licensing input, and is that requirement within reach of the monitoring technology now available?

The contribution is deliberately narrow. The study generates no primary field data and makes no estimate of Indonesian extraction volumes, because no such estimate can be made responsibly from the public record. Its contribution is the assembly of a verified evidence base on the extraction-supply relationship and the specification of the licensing parameters that a budget-referenced permit would require. That specification is offered as a design proposal to be tested, not as a validated instrument.

2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

Sand as a common-pool resource

Torres et al. (2017) supply the framing that organises this literature. They characterise sand as a common-pool resource: one whose users are rivalrous, since material removed by one operator is unavailable to another and unavailable to the river, but from which exclusion is expensive, because a riverbed cannot readily be fenced, monitored or attributed to an owner. Their estimate of 28.6 gigatonnes extracted annually, with aggregates constituting 79 per cent of the material used in buildings and transport infrastructure, established the order of magnitude for subsequent work.

The common-pool characterisation is doing analytical work rather than supplying a label. It identifies the conditions under which unregulated access produces depletion, and locates those conditions in the physical properties of the resource rather than in the failings of any particular jurisdiction. A country with capable regulators and a country without will face the same structural problem; they will differ only in how far they close the gap between the difficulty of exclusion and the incentive to extract.

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

Bendixen et al. (2019) sharpened the argument by observing that extraction now outpaces replacement and calling for coordinated global monitoring and management. Rentier and Cammeraat (2022), in the most systematic review available, map the environmental impacts of river sand mining across physical, biological, chemical and anthropogenic categories and conclude that the impacts are cumulative and difficult to quantify. Their review also records the quantities on which much of the subsequent debate rests: consumption near fifty gigatonnes annually, a projection of eighty-two gigatonnes by 2060, natural production replacing roughly half of extraction, and illegal sand mining occurring in approximately seventy countries.

The sediment budget as an accounting frame

The sediment budget states that the change in sediment stored within a defined river reach over a defined period equals the sediment entering the reach minus the sediment leaving it. Inputs comprise the load delivered from upstream, contributions from tributaries, and material supplied by bank erosion and hillslope processes within the reach. Outputs comprise the load transported downstream and the material removed by extraction. Where the sum of outputs exceeds the sum of inputs over a sustained period, the reach is in deficit and the bed necessarily lowers.

Three properties of this identity give it regulatory significance. First, it is scale-defined: a budget is computed for a specified reach, and a permit that does not specify the reach to which it corresponds cannot be evaluated against one. Second, it is cumulative: a deficit persisting across seasons produces an effect that a single season's data cannot detect, which means permits issued annually against annual observations will systematically miss the relevant trend. Third, it is spatially displaced in its consequences: because extraction reduces the load available for downstream transport, a reach in balance may nonetheless impose incision on reaches below it, so that the jurisdiction bearing the harm is often not the jurisdiction issuing the permit.

This last property is the one that most resists administrative accommodation. It means that the appropriate unit of licensing analysis is the basin or at minimum the sub-basin, whereas the unit of licensing authority is almost invariably a political jurisdiction whose boundaries a river crosses.

Measured physical impacts

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

Koehnken et al. (2020), reviewing the scientific evidence on freshwater ecosystems, identify channel incision as the most frequently documented physical impact of riverine extraction and note a research gap that qualifies the entire evidence base: the rivers for which the strongest evidence exists are not those where extraction is most intense. The documented record is therefore not a sample of the global condition but a sample of where measurement happened to be undertaken.

The Mekong provides the best-quantified case. Hackney et al. (2020) find extraction of approximately fifty million tonnes annually against a natural sand supply of 6.18 million tonnes, driving bed lowering averaging 0.13 metres per year and reaching 0.59 metres per year, with consequent bank instability threatening riverside settlements. The same study places global sand mining at roughly forty thousand million tonnes per year against total global fluvial sediment discharge of nineteen thousand million tonnes, a comparison whose implication is that humanity removes from rivers substantially more than rivers carry.

Hackney et al. (2021) extend the analysis using satellite observation of the Cambodian Mekong, finding extraction rising from 24 million tonnes in 2016 to 59 million tonnes in 2020, and only two of sixty observed months recording a positive sand budget. Two aspects of that result matter for the present argument. The trajectory, not merely the level, constitutes the finding; and the method demonstrates that a sediment budget can be constructed from remotely sensed data at monthly resolution, which is the technical precondition for using budgets administratively.

System-scale governance

Torres et al. (2021) argue that governance attention must shift from the individual extraction site to the regional sand-supply network understood as a coupled human-natural system, and identify three strategic action areas for doing so. Their argument follows from the physics rather than from institutional preference: because demand is met from whichever source is cheapest and impacts propagate downstream, site-level permitting cannot govern a system that operates at basin scale.

Bendixen et al. (2021) connect aggregate extraction to the sustainable development agenda, identifying conflicts and synergies across goals and noting that impacts fall most heavily on low- and middle-income countries. Lamb and Fung (2022), examining the Salween across the Myanmar-Thailand border, find state-centric transboundary governance frameworks failing to capture the relevant impacts because extraction is entangled with riverside

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

livelihoods and migration patterns that those frameworks do not see. Lamb et al. (2019) develop the same point for the global sand trade, arguing that local livelihoods are omitted from the policy calculation entirely.

Indonesian evidence

Indonesian research on sand extraction is predominantly social and economic rather than geomorphological, which is itself a finding about the state of the evidence. Purnomo et al. (2021) document village economies shifting from agriculture into sand mining driven principally by large-scale government infrastructure policy, with resistance cultural and passive and household adaptation short-term. Kusumaningrum et al. (2021) trace how the architectural transition from timber to concrete drove demand on the Jeneberang River, converting livelihoods from farming to extraction under rapid urbanisation. Untari et al. (2022) record sand mining emerging as a livelihood strategy inside a national park and Ramsar site, concluding that strengthening local institutions is a precondition for sustainable management.

On the regulatory side, Haq et al. (2023) identify inconsistent regulation as the principal obstacle to environmental management in a district case study and propose policy redesign to eliminate illegal operations. What none of this work supplies, and what is not available from any public Indonesian source located, is a sediment budget for any Indonesian river subject to extraction.

The supply side is falling as well

A sediment budget has two sides, and the literature reviewed above concentrates on withdrawal. The supply side is moving in the same direction. Chua and Lu (2022), examining the same basin at a long-monitored gauging station, find sediment load falling from 79 plus or minus 32 million tonnes per year in the period from 1965 to 1991 to 12.5 plus or minus 4.6 million tonnes per year between 2010 and 2019 — an eighty-four per cent decrease — attributed largely to upstream dam construction, with tributary buffering appearing temporary given further dams planned.

Shi and Qin (2023), reviewing 1,385 publications across fifteen years, establish the general mechanism: dams retain sediment and nutrients, greatly reducing loads delivered to coastal waters, with consequences that include reservoir capacity loss, downstream channel erosion, delta land loss and eutrophication. The implication for licensing is direct and unwelcome. A

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

reach's natural supply is not a fixed parameter to be measured once; it is itself declining where upstream impoundment continues, so an allowance set against a supply estimate becomes progressively more permissive unless the estimate is refreshed.

Park (2024) documents the extraction side in the delta of the same system, reporting an annual sand-mining budget between 8.5 and 45.7 million cubic metres, with the spread reflecting both differing estimation methods and pervasive unlicensed extraction. The consequences recorded include deeply incised riverbeds driving bank and coastal erosion, reduced water levels, disrupted hydrological connectivity and amplified dry-season saltwater intrusion through backwater effects. The volumetric basis of that estimate is worth noting: it is not directly comparable with mass figures without a stated bulk density.

Monitoring is now cheap enough to be a licensing input

The practical objection to budget-referenced permitting has always been measurement cost, and two studies indicate that the objection is weakening. Gruel and Latrubesse (2021) built a monitoring system from freely available radar satellite data that detected mining vessels across approximately 703 kilometres of channel over more than three years, finding eighty-two per cent of vessel activity occurring between November and June and half of all detected vessels concentrated within a 141-kilometre reach. Detection operated in near real time at satisfactory accuracy and at no data cost.

Diaconu et al. (2023) demonstrate the complementary capability at site scale, combining satellite imagery with uncrewed aerial survey to identify unlicensed extraction and quantify removed volumes of 314 cubic metres at one river site and approximately 4,881 cubic metres at another. Taken together, the two studies establish that both the reach-scale distribution of activity and the site-scale volume removed are now measurable by an enforcement agency without field instrumentation, which is precisely the unlicensed-extraction term the budget framework requires.

Tran et al. (2023) identify the social precondition that technical monitoring does not supply. Surveying residents along a heavily mined river, they find eighty-two per cent recognising that bank erosion had worsened but only eighteen per cent understanding the mechanism connecting it to extraction, with awareness rising mainly after personal property damage. A licensing regime that depends on local reporting of unlicensed activity therefore depends on an understanding that the evidence indicates is largely absent until harm has already occurred.

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

Research gap

Two gaps follow. The first is empirical and cannot be closed here: no sediment budget exists in the public record for Indonesian rivers under extraction, so the domestic scale of deficit is unknown rather than small. The second is a design gap, and it is the one this study addresses. The geomorphological literature establishes both the accounting identity and the feasibility of computing it from satellite data; the governance literature establishes that site-level volume permitting is inadequate. No located study specifies how the former would be converted into the parameters of the latter. That specification is the contribution attempted here.

3. METHOD

The study is a structured review with a secondary quantitative synthesis and a design-oriented analysis. It generates no primary field data, makes no estimate of extraction volumes for any Indonesian river, and does not test the instrument it proposes.

Literature identification and inclusion

Studies published between 2017 and 2024 addressing sand and aggregate extraction, river sediment dynamics, extraction governance and Indonesian mineral regulation were identified through academic databases and the reference chains of the review articles located. Inclusion required peer review, publication within the stated window, and bibliographic details that could be verified on a publisher page, a digital object identifier record or the journal's own site. Works whose indexing status or metadata proved inconsistent between sources were excluded rather than qualified.

Quantitative synthesis

Global and basin quantities were taken from the located peer-reviewed articles and from an international agency publication, with each figure traced to a single identified source rather than to secondary citation. Where two sources reported different values for the same quantity, both are reported with their sources rather than reconciled. The extraction-to-supply ratio for the lower Mekong is computed directly from the two published quantities and is the only calculation performed on the assembled figures.

Design analysis

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

The design component proceeds by taking the sediment budget identity as given and asking, for each of its terms, what a licensing authority would need to know, at what interval, and with what tolerance, in order to issue a permit that is defensible against the identity. The output is a parameter specification, not an estimate. Its validity claim is limited: it states what a budget-referenced permit would have to contain, not that such a permit would be effective if introduced.

What could not be verified

One category of figure common in this field is absent because it could not be verified. No reliable global estimate of the proportion of extraction that is illegal was located. The verifiable statement is that illegal sand mining occurs in approximately seventy countries, which describes distribution rather than proportion. Percentage claims about the illegal share circulate widely in secondary sources and are not used here. Likewise, no Indonesian extraction volume series of verifiable provenance was located, and none is reported.

4. RESULTS AND DISCUSSION

The global balance

The assembled quantities establish that aggregate extraction is not a marginal environmental issue but a material flow of first order, and that the flow is unbalanced at the global scale.

Table 1. Verified quantities on aggregate extraction and sediment supply

Quantity	Value	Source
Annual global extraction for construction	~50 billion tonnes	United Nations Environment Programme (2023)
Rank among extracted resources	Second, after water	United Nations Environment Programme (2023)
Annual growth in extraction rate	~6 per cent	United Nations Environment Programme (2023)
Projected consumption by 2060	82 gigatonnes	Rentier & Cammeraat (2022)
Natural production relative to extraction	About one half	Rentier & Cammeraat (2022)
Countries with illegal sand mining	Approximately 70	Rentier & Cammeraat (2022)
Aggregates as share of building and transport material	79 per cent	Torres et al. (2017)
Annual extraction estimate	28.6 gigatonnes	Torres et al. (2017)
Global sand mining vs fluvial sediment	~40,000 vs 19,000 Mt per year	Hackney et al. (2020)

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

discharge		

Source: compiled by the authors from the cited works. No verified global estimate of the illegal share of extraction was located. The two annual extraction estimates differ in scope and reference year and are reported as published rather than reconciled.

The comparison between global river extraction and total fluvial sediment discharge deserves particular emphasis, because it is the only figure in the table that expresses a budget rather than a level. Removal of roughly forty thousand million tonnes annually against a delivery of nineteen thousand million tonnes is not a resource being used somewhat faster than it regenerates. It is a resource whose regeneration is less than half the rate of use, which places the activity outside any conventional understanding of sustainable extraction and makes the deficit structural rather than cyclical.

The growth rate compounds this. Extraction rising at approximately six per cent annually doubles in under twelve years. A supply that is fixed by geological and hydrological processes cannot respond, so the ratio between removal and replenishment worsens mechanically with time even if no new extraction site is opened, simply because existing sites intensify.

Extraction against replenishment at basin scale

The Mekong evidence renders the global imbalance concrete and attaches it to measured physical consequences.

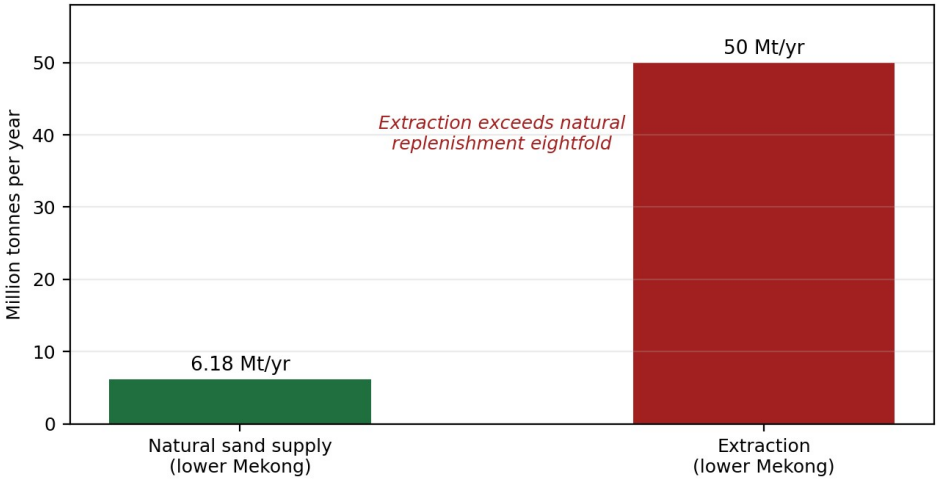


Figure 1. Sand extraction against natural supply, lower Mekong River (source: Hackney et al., 2020)

Extraction of fifty million tonnes annually against a natural supply of 6.18 million tonnes is a ratio of approximately eight to one. The physical consequence is measured rather than

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

modelled: bed lowering averaging 0.13 metres per year and reaching 0.59 metres per year in places, with bank collapse threatening riverside settlements. At an average of 0.13 metres, a decade of extraction at present rates lowers the bed by more than a metre, which is sufficient to disconnect floodplains, alter groundwater gradients and undermine bridge and embankment foundations designed for the previous bed elevation.

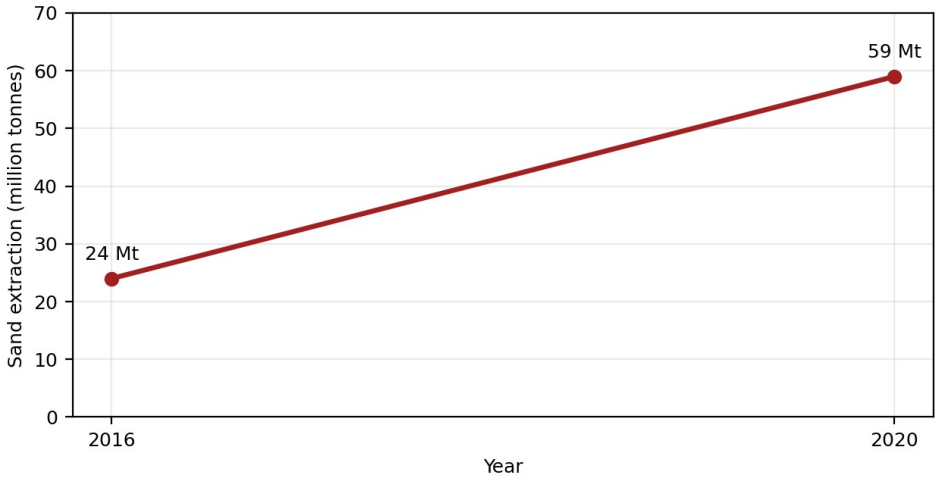


Figure 2. Sand extraction in the Cambodian Mekong, 2016 and 2020 (source: Hackney et al., 2021)

The Cambodian reach shows extraction rising from 24 to 59 million tonnes across four years, with only two of sixty observed months recording a positive sand budget. Two of sixty is the more informative statistic. It indicates that the deficit is not an occasional excess against a generally balanced system but the system's normal state, in which case the relevant policy question is not how to prevent occasional overextraction but how to return a permanently negative budget toward balance.

Koehnken et al.'s (2020) observation that the best-studied rivers are not the most heavily mined carries a specific implication for the present study. If measurement effort and extraction intensity are uncorrelated or negatively correlated, then the Mekong figures are not an upper bound on the global condition. Rivers where no budget has been computed may be in deeper deficit, and Indonesian rivers fall entirely within that unmeasured set.

From deficit to damage

The sediment budget explains why extraction produces the impact profile that the review literature documents. Each of the effects recorded by Rentier and Cammeraat (2022) and

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

Koehnken et al. (2020) follows from bed lowering or from the removal of the substrate itself, and their sequencing is what makes them difficult to govern through site-level permits.

Table 2. Impact pathways from a negative sediment budget

Pathway	Mechanism	Spatial expression	Reversibility on policy timescales
Channel incision	Output exceeds input; bed elevation falls	Extraction reach and downstream	Low
Bank instability and collapse	Loss of toe support as bed lowers	Extraction reach and downstream	Low
Water table decline	Channel bed falls below adjacent groundwater level	Riparian corridor	Low
Infrastructure undermining	Foundations exposed as bed lowers	Bridges, embankments, intakes	Only by reconstruction
Habitat and substrate loss	Removal of the bed material itself	Extraction site	Partial, slow
Delta and coastal sediment starvation	Reduced load delivered to the coast	Far downstream, coastal	Very low

Source: authors' synthesis of impact categories reported by Koehnken et al. (2020) and Rentier and Cammeraat (2022). Reversibility assessments are the authors' interpretation and are not quantified in the source literature.

Three features of this pathway structure defeat volume-based permitting. The impacts are cumulative, so no single permit produces an observable effect and each is therefore individually defensible. They are spatially displaced, so the harm appears where no permit was issued. And they are largely irreversible on the timescales over which permits are reviewed, so a regulatory system that corrects after detection corrects too late.

Why volume permits are not weak budget permits

It is tempting to treat a volume permit as a crude approximation of a budget permit — the same instrument with less information. The comparison in Table 3 indicates that this is mistaken. The two instruments differ in what they regulate, not merely in how precisely they regulate it.

Table 3. Volume-referenced and budget-referenced extraction permits compared

Design element	Volume-referenced permit	Budget-referenced permit
Quantity regulated	Operator entitlement	Reach deficit
Spatial unit	Licence area	Defined river reach within a basin
Information required	Site boundary; declared volume	Reach inputs, outputs and storage change
Aggregation across operators	None; permits assessed singly	Mandatory; all extraction in the reach

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

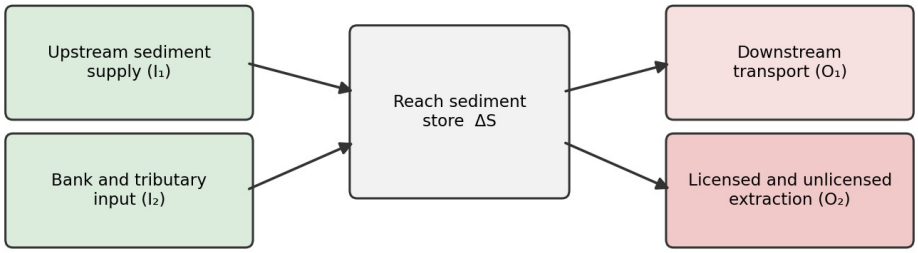
		summed
Treatment of unlicensed extraction	Outside the instrument	Must be estimated and deducted from the allowance
Review trigger	Permit expiry	Observed change in bed elevation or storage
Failure mode	Cumulative deficit invisible	Supply estimate error

Source: authors' analysis.

The decisive row is aggregation. A volume permit is assessed against the applicant; a budget permit is assessed against everything happening in the reach, including extraction by others and including extraction that holds no permit at all. This changes the administrative object from a file to a place, and it is the reason the transition is institutionally demanding rather than merely technically demanding.

The second consequential row is the treatment of unlicensed extraction. Under a volume regime, unlicensed extraction is an enforcement matter external to the permit. Under a budget regime it is an input to the permit calculation, because material removed without a licence depletes the reach exactly as licensed material does. A budget-referenced system must therefore estimate unlicensed removal in order to set licensed allowances, which converts enforcement data into a licensing requirement.

Operationalising the budget as a licensing parameter



$\Delta S = (I_1 + I_2) - (O_1 + O_2)$; $\Delta S < 0 \Rightarrow$ *bed incision, bank collapse*

A licensing decision sets O_2. It is defensible only if I_1, I_2 and O_1 are estimated.

Figure 3. The sediment budget identity and the term that licensing controls (authors' construction)

Figure 3 shows that a licensing authority controls exactly one term of the identity. Everything else must be estimated. Five parameters would have to be specified for a permit to be defensible against the identity.

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

The first is reach definition. A budget is computed for a bounded reach, so the licensing instrument must designate reaches as its spatial unit and assign every extraction site to one. Reaches should be delimited by hydrological rather than administrative criteria, which implies that where a reach crosses a jurisdictional boundary the permitting authorities must share the allowance rather than issue independently against the same reach.

The second is the supply estimate. Inputs from upstream, tributaries and bank erosion must be estimated for each reach at an interval no longer than the permit term. This is the parameter that has historically made budget-referenced permitting impractical, and it is the one the recent literature has changed: Hackney et al. (2021) construct a monthly budget from satellite observation, establishing that the estimate need not depend on continuous field gauging.

The third is deficit tolerance. A budget-referenced permit requires an explicit policy decision about how much deficit is acceptable and over what averaging period, because a rule of strict annual balance would prohibit extraction in most reaches while a rule with no ceiling would license the present situation. The tolerance is a normative choice that the science constrains but does not determine, and stating it explicitly is preferable to the current arrangement in which it is implied by whatever volumes happen to be permitted.

The fourth is the monitoring interval. Because the effect is cumulative, the interval must be short relative to the rate at which incision becomes irreversible. The Cambodian evidence, in which the sign of the monthly budget was negative in fifty-eight of sixty months, indicates that annual observation would have detected the deficit but would have concealed its consistency, and consistency is what distinguishes a structural deficit from a fluctuating one.

The fifth is the unlicensed-extraction allowance. Since unlicensed removal depletes the reach, the licensed allowance must be set net of an estimate of it. This has an uncomfortable but unavoidable implication: in a reach with substantial unlicensed extraction, the defensible licensed allowance is smaller than it would be in a well-policed reach with identical hydrology. Licensed operators would therefore bear the cost of enforcement failure, which creates a constituency for enforcement among the operators themselves — a consequence worth designing for deliberately rather than discovering.

Indonesian applicability

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

Applying this specification to Indonesia encounters a data condition rather than a conceptual obstacle. The extraction side of the identity is partially observable: licences record permitted volumes and district revenue assessment generates production figures, though neither captures unlicensed removal. The supply side is not observed at all in the public record. No sediment budget for an Indonesian river under extraction was located in this review.

The satellite methods demonstrated by Hackney et al. (2021) are not basin-specific and do not require instrumentation in place beforehand, which means the supply side is estimable retrospectively for rivers where extraction is already established. The practical entry point is therefore not a national programme but a single pilot reach on a river with known intensive extraction, computed for a period already covered by available imagery, with the resulting budget compared against the volumes licensed for that reach over the same period. That comparison is the minimum evidence needed to establish whether Indonesian licensing is issuing allowances above or below reach supply, and it is presently unknown in either direction.

The institutional complication is that the licensing authority for this mineral category and the authority holding production assessment data are different levels of government, so even the extraction side of the identity is not assembled in one place. That separation is a governance question beyond the scope of this study, but it bears on feasibility: a budget-referenced permit requires aggregation of all extraction in a reach, and no single authority currently holds the records that aggregation would need.

Limitations

Four limitations qualify these findings. First, the quantitative evidence is drawn overwhelmingly from one basin, and the reviewed literature itself warns that studied rivers are unrepresentative of mined rivers; the Mekong ratios should be read as a documented case rather than as a global parameter. Second, the impact pathways in Table 2 synthesise categories from review articles, and the reversibility column is the authors' interpretation rather than a quantified finding in the sources. Third, the parameter specification is a design proposal that has not been tested in any jurisdiction, and its administrative feasibility is asserted from the availability of the underlying measurement method rather than demonstrated. Fourth, no Indonesian data were available for any term of the identity, so the domestic argument rests on transferability of the method rather than on domestic evidence.

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

5. CONCLUSION

Extraction of sand and gravel is among the largest material flows humanity generates and among the least accounted for. Global consumption approaching fifty gigatonnes a year, growing at approximately six per cent, against natural replacement of roughly half, describes systematic drawdown; the comparison between some forty thousand million tonnes removed from rivers annually and nineteen thousand million tonnes delivered by them establishes that the deficit is structural. The lower Mekong, where extraction exceeds natural supply eightfold and only two of sixty observed months recorded a positive budget, shows what that means in a specific basin, together with the bed lowering of 0.13 metres per year that follows.

The central argument of this study is that volume-referenced permitting is not an approximate form of sediment management but a different exercise. It regulates operator entitlement, assesses permits singly, treats unlicensed extraction as external, and reviews at permit expiry. A budget-referenced permit regulates reach deficit, aggregates all extraction including the unlicensed, and reviews on observed change. No amount of tightening the first produces the second.

Converting the sediment budget into a licensing input requires five specified parameters: hydrologically defined reaches as the spatial unit, a periodic supply estimate, an explicit deficit tolerance, a monitoring interval short relative to the accumulation of irreversible change, and a licensed allowance set net of estimated unlicensed removal. The technical precondition for the second of these has recently been met, since sediment budgets can now be constructed from satellite observation at monthly resolution without prior instrumentation. For Indonesia, where no sediment budget for a river under extraction exists in the public record, the appropriate next step is not a national programme but a single pilot reach computed retrospectively and compared against the volumes licensed there. Until such a comparison is made, whether Indonesian extraction licensing operates within or beyond river supply is not a difficult question but an unasked one.

ACKNOWLEDGEMENTS

The authors thank the editorial team of Research Center Progresif for their assistance.

DECLARATIONS

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

Author contributions (CRediT)

Aloisius Yonathan Prakoso: conceptualisation; methodology; formal analysis; writing - original draft; writing - review and editing.

Conflict of interest

The authors declare that they have no competing interests.

Data availability

All data supporting the findings of this study are available within the article and from the publicly accessible sources cited therein.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declaration on the use of artificial intelligence

No generative artificial intelligence tool was used in the preparation of this manuscript.

REFERENCES

Bendixen, M., Best, J., Hackney, C., & Iversen, L. L. (2019). Time is running out for sand. Nature, 571(7763), 29-31. https://doi.org/10.1038/d41586-019-02042-4

Bendixen, M., Iversen, L. L., Best, J., Franks, D. M., Hackney, C. R., Latrubesse, E. M., & Tusting, L. S. (2021). Sand, gravel, and UN Sustainable Development Goals: Conflicts, synergies, and pathways forward. One Earth, 4(8), 1095-1111. https://doi.org/10.1016/j.oneear.2021.07.008

Chua, S. D. X., & Lu, X. X. (2022). Sediment load crisis in the Mekong River Basin: Severe reductions over the decades. Geomorphology, 419, 108484. https://doi.org/10.1016/j.geomorph.2022.108484

Diaconu, D. C., Koutalakis, P. D., Gkiatas, G. T., Dascalu, G. V., & Zaimes, G. N. (2023). River sand and gravel mining monitoring using remote sensing and UAVs. Sustainability, 15(3), 1944. https://doi.org/10.3390/su15031944

Gruel, C. R., & Latrubesse, E. M. (2021). A monitoring system of sand mining in large rivers and its application to the Ayeyarwady (Irrawaddy) River, Myanmar. Water, 13(17), 2331. https://doi.org/10.3390/w13172331

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

Hackney, C. R., Darby, S. E., Parsons, D. R., Leyland, J., Best, J. L., Aalto, R., Nicholas, A. P., & Houseago, R. C. (2020). River bank instability from unsustainable sand mining in the lower Mekong River. Nature Sustainability, 3(3), 217-225. https://doi.org/10.1038/s41893-019-0455-3

Hackney, C. R., Vasilopoulos, G., Heng, S., Darbari, V., Walker, S., & Parsons, D. R. (2021). Sand mining far outpaces natural supply in a large alluvial river. Earth Surface Dynamics, 9(5), 1323-1334. https://doi.org/10.5194/esurf-9-1323-2021

Haq, T., Hanani, N., Marjono, & Khusaini, M. (2023). Sustainable environmental recovery policy: Redesigning sand mining policy in Indonesia. Journal of Law and Sustainable Development, 11(7), e1311. https://doi.org/10.55908/sdgs.v11i7.1311

Koehnken, L., Rintoul, M. S., Goichot, M., Tickner, D., Loftus, A.-C., & Acreman, M. C. (2020). Impacts of riverine sand mining on freshwater ecosystems: A review of the scientific evidence and guidance for future research. River Research and Applications, 36(3), 362-370. https://doi.org/10.1002/rra.3586

Kusumaningrum, D., Hafsari, T. A., & Syam, L. (2021). Sand and the city: The historical geography of sand mining in Jeneberang River and its relation to urban development in South Sulawesi. ETNOSIA: Jurnal Etnografi Indonesia, 6(2), 200-216. https://doi.org/10.31947/etnosia.v6i2.17918

Lamb, V., & Fung, Z. (2022). Expanding transboundary environmental governance: A mobile political ecology of sand and shifting resource-based livelihoods in Southeast Asia. Environmental Policy and Governance, 32(4), 281-291. https://doi.org/10.1002/eet.1972

Lamb, V., Marschke, M., & Rigg, J. (2019). Trading sand, undermining lives: Omitted livelihoods in the global trade in sand. Annals of the American Association of Geographers, 109(5), 1511-1528. https://doi.org/10.1080/24694452.2018.1541401

Park, E. (2024). Sand mining in the Mekong Delta: Extent and compounded impacts. Science of the Total Environment, 924, 171620. https://doi.org/10.1016/j.scitotenv.2024.171620

Purnomo, M., Utomo, M. R., Pertiwi, V. A., Laili, F., Pariasa, I. I., Riyanto, S., Andriatmoko, N. D., & Handono, S. Y. (2021). Resistance to mining and adaptation of Indonesia farmer's household to economic vulnerability of small scale sand mining activities. Local Environment, 26(12), 1498-1511. https://doi.org/10.1080/13549839.2021.1990234

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0

Rentier, E. S., & Cammeraat, L. H. (2022). The environmental impacts of river sand mining. Science of the Total Environment, 838, 155877. https://doi.org/10.1016/j.scitotenv.2022.155877

Shi, W., & Qin, B. (2023). Sediment and nutrient trapping by river dams: A critical review based on 15-year big data. Current Pollution Reports, 9(2), 165-173. https://doi.org/10.1007/s40726-023-00258-7

Torres, A., Brandt, J., Lear, K., & Liu, J. (2017). A looming tragedy of the sand commons. Science, 357(6355), 970-971. https://doi.org/10.1126/science.aao0503

Torres, A., Simoni, M. U., Keiding, J. K., Muller, D. B., zu Ermgassen, S. O. S. E., Liu, J., Jaeger, J. A. G., Winter, M., & Lambin, E. F. (2021). Sustainability of the global sand system in the Anthropocene. One Earth, 4(5), 639-650. https://doi.org/10.1016/j.oneear.2021.04.011

Tran, D. D., Thien, N. D., Yuen, K. W., Lau, R. Y. S., Wang, J., & Park, E. (2023). Uncovering the lack of awareness of sand mining impacts on riverbank erosion among Mekong Delta residents: Insights from a comprehensive survey. Scientific Reports, 13, 15937. https://doi.org/10.1038/s41598-023-43114-w

Untari, Darma, R., Betaubun, P., Arief, A. A., & Fudjaja, L. (2022). Changing livelihood strategies in a conservation area: Fishers, farmers, and sand mining in Merauke, Indonesia. Forest and Society, 6(1). https://doi.org/10.24259/fs.v6i1.13868

e-ISSN 3165-3324 · Open access, CC BY-SA 4.0