

## Review article

# River Sand and Gravel Mining: Striking a Balance between Ecology and Economy

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### ABSTRACT

Sediments (sand and gravel) in rivers are integral to riverine ecosystems and a valuable human economic resource. Abstraction of sediments from rivers should be guided primarily by striking a balance between maintaining the ecological integrity of rivers and the need for economic development. Sediments must be abstracted judiciously and planned, based on a quantitative assessment of sediment dynamics of different kinds of rivers and the seasonal and inter-annual variation. Allocations for abstraction should be made based on the availability of sediments replenished every year by the river at various locations and a comprehensive cumulative EIA of the abstraction. Technologies such as drones can be used to map and monitor the extent of sediment deposits with the help of existing institutions.

**Key Words:** River sediments; Sand mining; EIA, Ecological Impacts; Hydrological Impacts; Socio-economic impacts; Policies

### INTRODUCTION

Rivers are an essential link in the global hydrological cycle. They carry runoff from precipitation over their basins to the oceans through a network of river channels, ever widening as they move downstream. Water moving in the river carries sediments whose size and amount depend upon the volume and velocity of flow and the gradient of the river bed. Solid particles with an average diameter of 0.2 to 2.0 mm are termed sand. In contrast, progressively larger particles are referred to as gravel (2-63 mm), cobble (64-256 mm), and boulder (>256 mm), while the finer particles are categorized as silt (2 to 0.002 mm) and clay (< 2 microns). Sand and gravel are usually called 'aggregates' in the construction industry and as sediments in the case of water bodies. Larger particles keep settling along the river and usually move relatively slowly along the river bed (hence categorized as bedload). In contrast, finer particles remain suspended in the water column and are carried further downstream. While in hilly and upper reaches with swift and turbulent stream flows, the bedload is comprised mainly of cobbles, pebbles, and gravel, and the lower reaches, with milder gradients, largely have sandy beds. Sediments that

move with the water downstream are continuously eroded into particles of smaller size. Suspended sediments are normally carried to the oceans or spread by floodwaters over land surfaces along the river's course.

Along with sediments also transported are - various nutrients in dissolved or adsorbed states, dissolved and particulate organic matter, a variety of unicellular or colonial micro-organisms, and the propagules (seeds, spores, and pollen) of a large diversity of flora and fauna inhabiting the river and its catchment.

### Sediments in the river ecology

Sediments (cobbles to sand and clay) are an integral part of the river ecosystem and play an important role in their structure and functioning (Hauer et al. 2018). Interacting with the geology, flow regime, and bed gradient (slope), sediments determine the morphology and behavior of the river channel. Channels are usually classified into rocky, gravel, and sandy bed channels according to their bed characteristics. Sediments (load and particle size) are decisive in regulating flora and fauna diversity, composition, and habitat quality. Large aggregates from boulders to pebbles provide substrate for

epilithic forms such as diatoms, various other algae, bryophytes, and mosses. Many macrophytes also prefer different sediments; for example, members of the family Podostemaceae occur on rocks and boulders under waterfalls. The structure of benthic macroinvertebrate communities depends on sediment characteristics and the spatial pattern of their habitat and food. Numerous invertebrates and their young find refuge behind and between the boulders, cobbles, and pebbles. Similarly, various macroinvertebrates and fish possess morphological adaptations and require different kinds of sediments at different life stages. At the same time, certain benthic organisms help stabilise gravel sediments. Many fish utilise the coarse substrates for spawning and movement. Amongst higher vertebrates, turtles and alligators (including gharial) require sand for nesting and hard substrates for resting. Besides fauna, riparian plant communities are also adapted to different kinds of sediments and contribute to the provision of various ecosystem services, the most important being providing food and habitat for riverine biodiversity, prevention of bank erosion, and improving water quality.

Sediments, particularly the finer sand, silt, and clay, also play an important role in nutrient dynamics within the river system, influencing water quality. For example, clay adsorbs significant amounts of phosphates and may immobilize or remobilize them. Vegetation on sand bars has been demonstrated to help in denitrification. Similarly, the hyporheic fauna inhabiting different strata on bed sediments feed on organic particles and help improve water quality. Further, sediments hold large amounts of water (according to their particle size and total amount) and constitute a link with the groundwater. In alluvial rivers in particular, they play a major role in groundwater recharge.

### **Sediments: A renewable resource**

Sediments are a natural and renewable resource in as much as they are generated regularly (often continuously) by the weathering, crushing of rocks, and sorting with the flow of rivers. The number of sediments generated and transported by rivers varies greatly depending on geology, climate, catchment area, channel slope, flow regime, and 'stream power.' Stream Power is the ability of a stream to erode

material from its bed and banks or deposit the material on it. It is directly related to stream discharge ( $m^3/s$ ) and bed slope. Anthropogenic activities in the catchment, from deforestation and grazing to agriculture, mining, and urban development, also accelerate erosion and, hence, the sediment load in rivers and streams.

The transport of sediments downstream slows down when water flow velocity in river channels decreases due to low bed gradients. Rivers dump these sediments along the bed, creating islands and gravel or sand bars. Braiding of the river channel starts when the channels are wide but shallow, the bed slope is rather small, and river banks are readily erodible. During floods, rivers deposit sediments in sheets across the floodplain that builds up over time. Lateral shifting of river channels over the long term results in the formation of floodplain terraces.

### **Sand mining**

For centuries, sand has been treated as an economic resource, as sand and gravel removed from river shores have been used to construct buildings, bridges, roads, and other structures. Local governments regulated these sediments' abstraction in the past for revenue (Bendixen et al. 2021). Sand and gravel are now considered 'minor minerals' despite their widespread occurrence, abstraction, use, and relatively high monetary value. Accordingly, the term 'Mining' is used for their abstraction without a proper understanding of the many major differences between sand and gravel on one hand and other minerals (including coal) on the other (Table 1). Given these differences between the abstraction of sand/gravel and minerals, the term 'Mining' is a misnomer. Abstraction of groundwater, petroleum, natural gas, or even clay for bricks is not considered 'Mining'.

### **Impacts of sand/gravel mining**

In recent decades, the demand for river sediments has grown manifold with rapid increase in the construction industry and housing and infrastructure projects throughout developing countries. This has resulted in indiscriminate and excessive abstraction of sediments. The advent of mechanised abstraction using JCB excavators has allowed sand and gravel to be abstracted from greater depths and channels

Table 1. Comparison between sand + gravel and other minerals

<b>River sand + gravel</b>	<b>Minerals (metallic &amp; non-metallic; coal)</b>
Abstraction seasonal	Abstraction throughout the year
Sediments replenished during high flows	Minerals are not replenished
Rivers may shift course between states / districts	No shifting whatsoever of the deposit
Mine closure not required – self closure	Mine closure required
Short duration leases (3-5 years)	Long term leases (for decades) required
Abstraction usually restricted to a few meters depth, including the surface layer	Minerals abstracted from deeper layers of the earth
Very small or negligible investment required for abstraction	Huge investment required for abstraction
Surface layer removal not required; if vegetal cover present, sediments should not be abstracted	Surface soil/vegetation to be removed
Quality influenced by human activity(e.g. domestic/industrial waste disposal; agrochemicals used in agriculture)	Quality not influenced by human activity
Flora and fauna both on the surface and inside the sediment deposits are affected/disturbed	Flora and fauna on the surface affected adversely

underwater. In many cases, abstraction continues to depths below the groundwater table. United Nations agencies have now raised serious concerns about the issue (Anonymous 2019), and discussions on the conflicting impacts on the environment and humans, as well as on the obstacles to a sustainable future for this resource, are under discussion (Bendixen et al. 2021)

Similar to the impacts on rivers caused by excessive abstraction and diversion of water flows, the removal of sediments also has numerous physical, ecological, sociocultural, and economic impacts on riverine ecosystems (Rentier and Cammeraat 2022) and the people dependent upon them (Table 2). The reduction of sediments in rivers is also occurring rapidly due to their being trapped behind dams and weirs (Gupta et al. 2012).

The severity of impact depends upon the areal extent, magnitude, intensity, and depth of dredging operations, the nature of the river bed, bedload sediments, sand and gravel deposits, and the morphology of the river itself. Indiscriminate and unplanned abstraction of sand and gravel from active channels and floodplains is a disastrous activity and threatens the very existence of the river ecosystem. The problem is naturally most severe in smaller rivers with small catchments and, hence, limited recurrent supplies of sediment (Padmalal and Maya 2014).

Excessive (relative to the annual input) and large-scale extraction of river sediments by dredging below the streambed is the most important cause of changes in channel-bed form and shape, which lead to erosion of channel bed and banks, increase in slope, and change in channel morphology. Further changes include the undercutting and collapse of river banks, loss of adjacent land and structures, both upstream and downstream erosion, and changes in patterns of sediment deposition downstream and in channel beds and habitats. The abstraction of channel substrate, resuspension of streambed sediments, clearance of vegetation, and stockpiling on the streambed cause direct loss of stream habitat, disturbance to benthic species, and reduction in light penetration, primary production, and food availability (Bhattacharya and Chatterjee 2021). The foregoing impacts, in conjunction with dredging and associated activities, also result in water quality degradation in the river and groundwater (Mandaric et al. 2016).

However, it may be stressed that despite serious concerns expressed by various sections of society, and several restrictions imposed by the Government and the Courts on sand mining, there is a near-total lack of scientific, systematic investigations on the adverse impacts of river sediment abstraction in most developing countries, and especially in India (Koehnken et al. 2020, Melissa and Rousseau 2022,

Table 2. Impacts of gravel and sand mining from rivers (modified from Koehnken and Rintoul 2019, Koehnken et al. 2020)

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### Geomorphological Impacts

- Channel bed incision and shifting
- Alteration of channel-bed form and shape
- Lateral migration of river channel into the pit
- Failure of pit walls and consequent channel changes
- Enhanced erosion by receding floods

### Hydrological / Hydraulic Impacts

- Alteration of floodplain hydraulics during high flows
- Diversion or change of flow paths under flood conditions
- Clogging of river bottom sediments by deposition of fine particles
- Decline in groundwater recharge
- Reduced groundwater levels on adjacent areas
- Change in groundwater quality

### Ecological Impacts

- Loss of riparian habitat and vegetation
- Loss of floodplain habitat and vegetation
- Loss of in-stream habitats
- Loss of biodiversity (mainly fish and invertebrates)
- Disturbance to or reduction in resting, nesting, breeding and feeding sites of vertebrate fauna
- Potential impacts on rare and threatened species
- Reduction in planktonic populations due to turbidity and consequent food web changes
- Loss of hyporheic fauna
- Reduction in self-assimilation capacity

### Social and Economic Impacts

- Loss of agricultural land and production
  - Compaction of floodplain soils by heavy machinery
  - Disturbance of heritage values
  - Disturbance of cultural values
  - Changes in aesthetics, particularly in scenic quality
  - Increase in noise and dust
  - Health impacts on workers
  - Social, often violent, conflicts
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Rentier and Cammeraat 2022).

### Management of sediments

On the one hand, sediments are an integral component of the river ecosystem, maintaining the ecological integrity of rivers, but they are also an important natural resource for humans. While the over-abstraction of sediments, directly and indirectly, threatens the river ecosystem, severe ecological damage often occurs rapidly through their accumulation, causing aggradation of the river bed

and blocking of high flows, especially in the case of rivers with high sediment loads. Sediments in rivers, therefore, must be managed by striking a proper balance between their ecological and economic functions.

An assessment of the economics of sediment abstraction needs to consider the economic value of rivers' many indirect and intangible ecosystem services as mediated by their sediments, as well as the economic losses that may be caused by non-abstraction.

### Current management guidelines

The management of sand mining (or sediment management) has been discussed on a global scale (Anonymous 2019) in a report that focuses on (a) reduction in consumption, (b) finding alternative materials, (c) recycling and reuse of construction wastes, and (d) reducing impacts of extraction by following 'best practices'. Some countries have developed country-specific management guidelines, such as the USA (Meador and Layher 1998) and Malaysia (Anonymous 2009). In India, following the interventions of the National Green Tribunal and numerous incidents involving 'illegal' sand mining, a few guidelines have been issued by the Ministry of Environment, Forests and Climate Change (Anonymous 2016, 2020), Ministry of Water Resources (Anonymous 2017), and the Ministry of Mines (Anonymous 2018).

All guidelines mention the 'Sustainability' of sand mining but are focused on regulating and monitoring sand/ gravel removal activity across the country, hosting governance primarily with the district-level administration. Both land and water are state subjects under the Indian constitution, and various state governments have their own rules and regulations, which remain at variance with those of the central ministries (Anonymous 2018).

The MOEF-CC Guidelines (Anonymous 2016) mention the importance of "mining out material only that much which is deposited annually". The guidelines also discuss ways and means for assessing replenishment, stringent monitoring of areas leased for mining, prohibiting or protecting areas identified as important wildlife habitats, etc. Surprisingly, the MOEF-CC (2020) guidelines also state, "The purpose of mining in the river bed is for channelization of rivers so as to avoid the possibility of flooding and to maintain the flow of the rivers".

On the other hand, the Ministry of Water Resources (Anonymous 2017) clearly states in its Draft Policy on Sediment Management that "Dredging for desilting of Indian rivers may be adopted only in exceptional circumstances or when no other sustainable alternative is available". As commonly observed, the resulting mining in the main channel is eventually a significant cause of channel incision and shifting.

The Guidelines do not make any distinction between rivers by their order, geology, geomorphology, headwater areas or catchments, climate across the basin, valley shape, channel width, stream bed characteristics (rocky, gravel, alluvial), slope gradient, flow regime, riparian vegetation, floodplains, river pool sequence, or any other feature of river morphology. The Guidelines recognise no difference between Himalayan rivers' extensive alluvial floodplains and the rocky, relatively narrow valley peninsular rivers with low sediment loads.

Furthermore, the Guidelines do not consider the case of rivers, which shift their course regularly, sometimes annually. In many cases, rivers form the boundaries between districts and states. The Guidelines remain silent over the jurisdiction of district authorities and lessees after incidences of shifting of river channels and sand deposits. Anthropogenic activities further influence the amount of sand in the catchment. Sand/gravel quality is related to geology, mineral composition of the rocks, and water quality (which is altered by inflows of domestic and industrial wastes). Differences between the sand of the rivers Ganga and Yamuna are well known. Sand from the Ken (a tributary of the Yamuna), abstracted in the Banda district, is supplied right up to the northern districts of Uttar Pradesh as it is valued far more than the Ganga sand. Sand abstracted from the Yamuna has a relatively high salt content, as with sand in the Luni river basin.

The MOEF Guidelines recognize that the sediment's replenishment period may vary depending on the channel's nature and the season of deposition that arises due to variation in the flow. Such periods and seasons may vary depending on the geographical and precipitation characteristics of the region. However, these very factors have yet to be considered while developing systems to grant leases for abstraction. A lease period of 3 to 5 years means that while the sediments may not be replenished, intensive abstraction will continue even during periods of low flow. The Guidelines do not suggest a time gap between the allocation and re-allocation, or renewal of leases to allow for adequate replenishment, therefore wholly ignoring the issue of sustainability and river conservation.

The guidelines further state, "Sand and gravel may be extracted across the entire active channel

during the dry season.” This aligns intending to channelise the rivers, as pointed out earlier. Similarly, the MOEF Guidelines categorize leases for abstraction based on the area (5 to 100 ha or more) irrespective of river order, size, width, and bed characteristics. It is easy enough to understand the fate of a 25-m-wide stream where a 5 ha area is allowed to be ‘mined’ across the entire channel to a depth of about 3 m. The lessee then can dredge the stream over a two km length if sediments are available.

Another area for improvement with these Guidelines is permission to remove sand from the floodplains and terraces under agricultural fields. As alluvial rivers like the Yamuna have shifted many kilometers over the past few centuries and formed terraces, thick deposits of sand (often with intervening layers of clay or silt) lie below the present ground level. Removal of sand from these fields goes against floodplain conservation’s fundamental objectives for managing river water quality and biodiversity. The Guidelines as they currently are, despite their best intentions to check indiscriminate abstraction and regulate the process, are more likely to be a prescription for disaster in most cases, as they treat all rivers in India without discrimination - from north to south, east to west, or by size or origin.

### **Suggestions for sediment management**

Rivers can sustain the abstraction of sediments if the volumes are within the limits of annual replenishment in specific reaches and within the constraints of natural variability of the sediment load.

It is not the abstraction that impacts the river but the mining process and magnitude carried out without a scientific understanding of the rivers and their behaviour. Indian rivers, both the Himalayan and Peninsular Rivers, differ from other rivers worldwide. Ganga and Brahmaputra carry the world’s most considerable sediment load to the oceans – about 25% of the total sediment entering the world’s oceans. The monsoonal climate ensures extreme seasonal variability in flow regimes and, therefore, in the sediment load. This sediment load varies between reaches and generally increases considerably with the contribution made by the tributaries (Table 3).

Some suggestions are listed below in light of the foregoing discussion:

- @ Differentiate between and classify the rivers and their different reaches according to their potential for sediment transport and their seasonal and inter-annual variability.
- @ Extensive studies should be undertaken on the channel morphology of every river with gravel or sand mining potential; map the areas for sediment accumulation, meandering, flow pattern, riparian vegetation, significant biota, and catchment influences. These maps with baseline information should guide authorities before decisions on leases.
- @ Create a database for annual replenishment of sediments in all river stretches, together with information on flow variability and susceptibility of streams to shifting.
- @ Extraction permits must be based on a scientific assessment of annual replenishment and a comprehensive cumulative EIA of abstraction, incorporating impacts on channel morphology, biota (including riparian and hyporheic organisms), water quality, and groundwater recharge. Sediment abstraction sites should be clearly demarcated, and the data (with maps) should be placed in the public domain in local languages.
- @ Mark all the zones of aggradation along the river.
- @ The most sustainable way of sand extraction is Bar Skimming. Mark the baseline for scraping/skimming after accounting for the bedload, and maintain a record of sediments abstracted from each identified stretch.
- @ Determine the mining depth from the accumulation rate at particular locations without change in the slope of the stretch.
- @ The use of excavators and heavy machinery should be prohibited except in cases where extensive deposits are available for abstraction every year.
- @ Continuously monitors the river form and position of the sand mining areas, both upstream and downstream.
- @ Leave the main channel undisturbed. It should not be dredged unless there is significant aggradation causing a reduction in the slope gradient.
- @ Identify ecologically important sites along the river and prohibit sand extraction in those stretches, as well as 1.0 to 0.5 km stretches both up and downstream of these sites.
- @ Allow time for replenishment of sediments while keeping periods with low discharge in view. Decide and/ or modify the terms of leases every year as soon as the monsoon withdraws.
- @ New technologies such as drones may be used to map and monitor the extent of sediment deposits with the help of existing institutions. Satellite-based monitoring may be used over larger stretches.

Table 3. Examples of total sediment load (million tons per year) in Indian rivers and their tributaries (from Subramanian 1993, 1996). Values marked with \* are annual erosion rates (tons per km<sup>2</sup> catchment) from Subramanian (1978), \*\* from Sinha et al. (2019)

River	Sediment load
Indus	100
Jhelum	40.0*
Ganga	329
Yamuna	140 (at Allahabad)
Ken	7.0*
Betwa	4.0*
Son	3820*
Kosi	100 (at Chatara)**
Gandak	130.0*
Gomti	7 (at Lucknow)
Brahmaputra	597
Mahanadi	1.9
Godavari	170
Krishna	4
Tapti	25
Kaveri	1.5
Narmada	70
Mahi	9.7
Brahmani	20.4

### Emergent considerations

The construction of many dams and barrages has significantly reduced sediment loads in rivers (Gupta et al. 2012). Hence, the past data will not help determine sediment potential. More importantly, existing sediment monitoring stations need to be improved and cannot provide data of any significance for planning sustainable abstraction. For example, the sediment load of River Ken is monitored only at Banda, near the river's end. This data does not account for the vast amounts of sediments abstracted upstream in many 'sand mines' mined by local people or the sand trapped behind the two weirs and several dams on its tributaries.

Further, climate change scenarios, which project significant changes in the rainfall and runoff patterns in different parts of various river basins, are furthermore bound to affect the amounts and patterns of sediment loads in the rivers (Gosain et al. 2011,

Nepal and Shrestha 2015, Singh and Kumar 2018). These anticipated changes need to be considered in any long-term sediment management planning.

### Reduce, recycle, reuse, and other alternatives

In countries like India, which have yet to meet SDG 11's target 11.1 of 'ensuring access for all to adequate, safe and affordable housing by 2030', it is futile to think of a reduction in the demand for aggregates (sand and gravel). India has already embarked upon a housing scheme under PM Awas Yojna and PM Gramin Awas Yojana. The current emphasis on high-rise buildings and numerous infrastructure projects precludes any demand reduction.

An alternative is the abstraction by dredging out massive deposits of sediments in the reservoirs behind the dams and barrages. Given the high sedimentation rates of Indian reservoirs, this seems to be a desirable option. However, while this might be possible in the case of shallow reservoirs, it is nearly impossible to operate the dredgers in large, deep reservoirs, most of which lie in hilly regions. Besides the practicality and cost of abstraction, transporting abstracted sediments to the use sites will cause multiple serious problems.

Among other alternatives is the proposal for the recycling and reusing of construction wastes (Anonymous 2019) to produce manufactured sand (m-sand). As with other kinds of waste, it is a desirable and noble goal. However, one must examine the pollution potential of the recycling process that uses chemicals, water, and energy and generates large volumes of fine clay that clogs field soils and river beds, kills all life, and pollutes water. The solution to one ill should not create another plethora of problems. Various other substitutes, such as fly ash, coconut shells, and foundry wastes, have also been suggested for sand and gravel (Anonymous 2019) with little consideration of the properties of the concrete.

However, another kind of manufactured sand is the one that is produced as a by-product from crushers of stones, rocks, and boulders for making grit (coarse gravel). These crushers already operate in many parts of the country. They create an enormous air pollution problem through fine particulate dust that settles on vegetation, roads, fields, and water bodies and causes severe respiratory

disorders among humans and cattle. Apart from these impacts, the advocates of m-sand seem to ignore the environmental consequences of large-scale stone quarries - from the denudation of hills to the complete disappearance of smaller hills. Using the boulders or large gravel abstracted from the river beds to produce m-sand is also in no way justifiable.

## CONCLUSIONS

Sand and gravel are important natural, renewable economic resources whose indiscriminate and unplanned excessive abstraction threatens rivers' ecological integrity, biodiversity, and ecosystem services. There is an urgent need to balance the economy and ecology of river sediments through judicious, planned abstraction based on quantitative assessment of annual replenishments in different locations and years, along with a thorough cumulative EIA of such abstractions.

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