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RESEARCH ARTICLE

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Impacts of riverine sand mining on freshwater ecosystems: A review of the scientific evidence and guidance for future research

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Abstract

Sand mining (used here as a generic term that includes mining of any riverine aggregates regardless of particle size) is a global activity that is receiving increasing media attention due to perceived negative environmental and social impacts. As calls grow for stronger regulation of mining, there is a need to understand the scientific evidence to support effective management. This paper summarizes the results of a structured literature review addressing the question, "What evidence is there of impacts of sand mining on ecosystem structure, process, and biodiversity in rivers, floodplains, and estuaries?" The review found that most investigations have focused on temperate rivers where sand mining occurred historically but has now ceased. Channel incision was the most common physical impact identified; other physical responses, including habitat disturbance, alteration of riparian zones, and changes to downstream sediment transport, were highly variable and dependant on river characteristics. Ecosystem attributes affected included macroinvertebrate drift, fish movements, species abundance and community structures, and food web dynamics. Studies often inferred impacts on populations, but supporting data were scarce. Limited evidence suggests that rivers can sustain extraction if volumes are within the natural sediment load variability. Significantly, the countries and rivers for which there is science-based evidence related to sand mining are *not* those where extensive sand mining is currently reported. The lack of scientific and systematic studies of sand mining in these countries prevents accurate quantification of mined volumes or the type, extent, and magnitude of any impacts. Additional research into how sand mining is affecting ecosystem services, impacting biodiversity and particularly threatened species, and how mining impacts interact with other activities or threats is urgently required.

KEYWORDS

aggregate mining, ecosystems, rivers, sand mining, systematic review

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1 | INTRODUCTION

The rapid rise in urbanization and construction of large-scale infrastructure projects are driving increasing demands for construction materials globally. United Nations Environment Programme (UNEP; 2014) estimated that between 32 and 50 billion tonnes of sand and gravel are extracted globally each year with demand increasing, especially in developing countries (Schandl et al., 2016).

Rivers are a major source of sand and gravel for numerous reasons: cities tend to be located near rivers so transport costs are low; river energy grinds rocks into gravels and sands, thus eliminating the cost of mining, grinding, and sorting rocks; and the material produced by rivers tends to consist of resilient minerals of angular shape that are preferred for construction (whereas wind-blown deposits in deserts are rounder and less suitable). Here, we use "sand mining" as a generic term to embrace extraction of riverine aggregates regardless of particle size. Sand mining activities are one of many recognized pressures affecting riverine ecosystems, where biodiversity is already in rapid decline (World Wildlife Fund, 2018). Increasingly, there are media reports about the negative environmental and social impacts of sand mining, and as calls grow for stronger regulation of mining (Schandl et al., 2016), there is a need to understand the scientific evidence of mining impacts to underpin management.

Impacts of sand mining on rivers may be direct or indirect (Figure 1). Direct impacts are those in which the extraction of material is directly responsible for the ecosystem impact, such as due to the removal of floodplains habitat. Indirect impacts are related to ecosystem changes that are propagated through the system due to physical changes in the river system resulting from sand extraction. For example, the removal of material from a river can alter the channel, river hydraulics, or sediment budget which in turn can alter the distribution of habitats and ecosystem functioning. These types of impacts can be difficult to attribute to sand mining, as they may require long time frames to emerge, and other interventions can result in similar changes. The situation is further complicated by the existence of geomorphic thresholds in river systems (Schumm, 1979). Alterations linked to removal of sand from rivers may not be gradual and/or linear, and only limited changes may be observed for an extended period, but once a threshold is reached, change may become rapid and irreversible. Whether the impacts of sand mining are positive, neutral, or negative depends on the situation and perceptions of different stakeholders. For example, river incision could be perceived as positive by stakeholders if it reduces flood risk; however, for this review, we have considered a change from natural or decline in geomorphic or ecosystem characteristics as negative.

This paper summarizes the results of a literature review into the impacts of riverine sand mining on freshwater ecosystems. The aim of the review was to provide an understanding of the range of observed impacts related to sand mining activities and to guide future research directions.

2 | METHODOLOGY

The Quick Scoping Review (QSR) approach was adopted for this review. A QSR "aims to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to a question" (Collins, Coughlin, Miller, & Kirk, 2015). The QSR approach is structured by identifying a central question and defining the Population, Intervention, Comparator, and Outcome (PICO) related to the query. The central question identified for this

TABLE 1 Summary of QSR question and PICO elements

Question	What is the evidence of the impacts of sand mining on ecosystem structure, process, and biodiversity in rivers, floodplains, and estuaries?
Population	All rivers (including their floodplains) and estuaries of the world documented in papers and reports are available on the Web of Knowledge and SCOPUS written in English
Intervention	Removal of large quantities of sand or gravel
Comparator	Preextraction and postextraction conditions at a site or reference condition and postextraction condition
Outcome	Change in river, estuarine, or floodplain ecosystem

Source: After Collins et al. (2015).
Abbreviation: QSR, Quick Scoping Review.

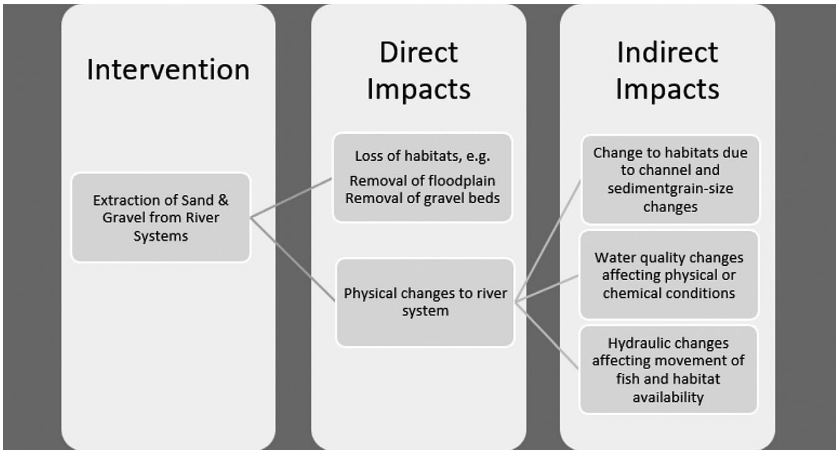

FIGURE 1 Schematic of the simple conceptual model used to define the Quick Scoping Review question and PICO elements. Direct and indirect impacts listed are provided as examples and are not an exhaustive list

review was, “What is the evidence of the impacts of sand mining on ecosystem structure, process, and biodiversity in rivers, floodplains, and estuaries, in relation to the PICO elements listed in Table 1?” This question focused on identifying papers in scientific publications that directly linked sand mining with ecological impacts and does not include scientific papers that only report the physical changes within river systems associated with sand extraction, of which there are many. Nor does it capture investigations identifying changes to ecosystem structure, process, or biodiversity that are linked to physical changes in rivers not caused by sand mining. Papers were excluded that inferred impacts but did not have quantitative evidence. Papers that fulfilled these inclusion criteria were categorized (publication date, location, type of system, study method, type and scale of extraction, presence of other stressors, the comparator employed, and the physical or biological impacts on the system) and included in the analysis. Details of the QSR methodology, including a table listing the search criteria, identified papers, and their characteristics are available as supporting information.

3 | RESULTS

3.1 | Description of papers

The search initially identified 505 papers, with 62 evaluated as applicable to the QSR question. Metrics of the papers are summarized in Figure 2 and in the Table 2 of the supplementary information. The relatively low number of investigations that address both aspects of the question likely reflects the interdisciplinary requirements of such an investigation, the different timescales over which geomorphic and ecological processes may operate, and the fundamental complexities of linking physical and ecological processes. The distribution of publication dates shows an increase in the number of relevant papers over time, with about 75% of the papers published within the last 5 years. This trend of increasing papers may reflect an increase in awareness of sand mining as an environmental issue. Most papers focused on the river systems in Europe (23) and North America (16). Papers related to

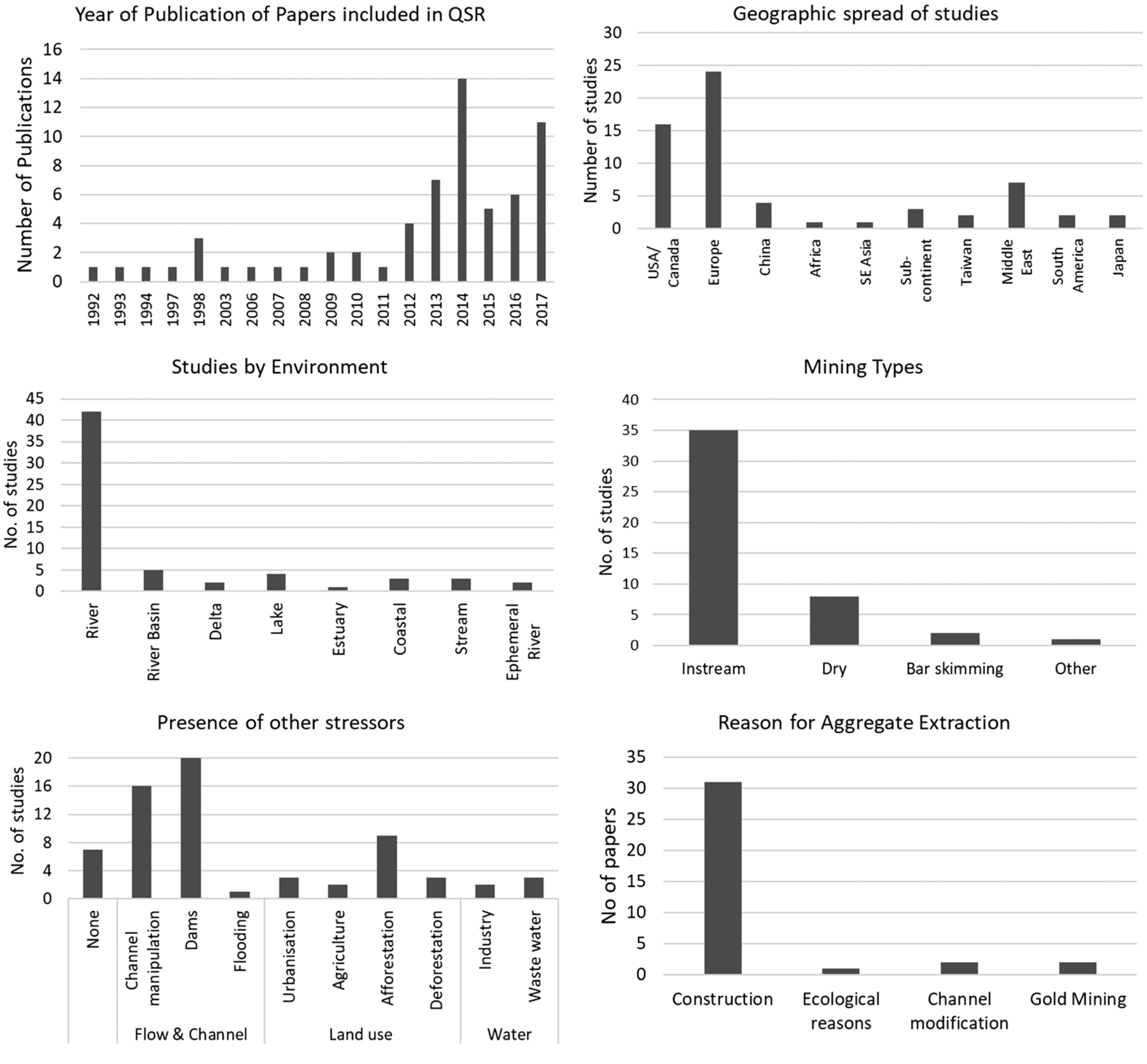

FIGURE 2 Metrics of the papers included in the structured Quick Scoping Review

Western Europe (10 of 17) predominantly focused on rivers in mountainous areas. In North America, Californian rivers received the most attention, with multiple studies also considering the Allegheny River in Pennsylvania. In 2014, California and Pennsylvania were the second and third highest producers of sand and gravel for construction in the United States behind Texas; hence, this focus may reflect the quantities removed. The small number of studies obtained from many regions of the world makes it difficult to determine why a few rivers have received a disproportionately large amount of attention, whereas others appear to have been ignored. This apparent bias may be attributable to limiting the QSR search to papers in English or research funding available in certain countries. It also may reflect the distribution of interested researchers.

Most investigations focused on reaches within one river or from multiple rivers. Five studies considered complete river catchments and considered other factors in addition to sand mining, such as land use changes, making attribution of impacts to individual stressors difficult. Four studies examined lakes (three focused on Lake Poyang, China), whereas deltas, estuaries, streams, ephemeral rivers, and coastal environments received less attention. The studies that considered single or multiple rivers generally did so by investigating a limited number of river reaches. This approach reflects the availability of historical information. Although reach specific investigations document local impacts of sand mining, they do not provide information about more distal impacts, such as delta or coastal shoreline starvation, or upstream or downstream morphological changes to river channels.

Of the studies reporting the type of mining, most focused on instream mining. Eight focused on the impacts of dry mining (removal of material from an exposed area above the water table, such as on a floodplain), with only two addressing bar skimming (removal of sand and gravel from the surface of exposed river bars). Several studies reported the effects of multiple types of mining.

The quantities of extracted material from rivers were reported by only 20 of the 63 studies with many cautioning that the reported values did not include quantities of illegally mined material, which were considered significant in certain regions. Extracted quantities from individual waterways ranged from <10,000 m^3 $year^{-1}$ to >230 million m^3 $year^{-1}$. Some of the smaller volumes, in the range of 5,000–8,000 m^3 $year^{-1}$ (Kondolf, 1993) were associated with channel maintenance for flood control in aggrading rivers. By far, the largest reported volumes are those extracted from Poyang Lake in China, where over 1,800 Mm^3 of material is estimated to have been extracted at a rate of about 235 Mm^3 $year^{-1}$ in under a decade (Lai et al., 2014). Construction material was reported as the primary use in almost all studies.

Nine different investigative methods for determining changes associated with sand mining were captured in the QSR, with the most common inference method being the comparison of current conditions to historical images and maps to identify changes on annual to decadal timescales. An approach that was slightly less common was the monitoring of biological and ecological factors. Other common methods included measuring water quality indicators and changes in geomorphological and hydrodynamic features.

3.2 | Abiotic impacts to river systems

A total of 107 different impacts were documented by the investigations. The abiotic impacts were broadly divided between changes to the channel morphology, alterations to the composition and movement of sediment, changes to larger scale river features, alterations to the flow regime, and impacts on water quality (Figure 3).

The most prevalent impacts were changes to channel morphology, with channel incision most common. Contrasting impacts were reported from different systems reflecting the site-specific nature of impacts, including channel widening and narrowing, reductions or

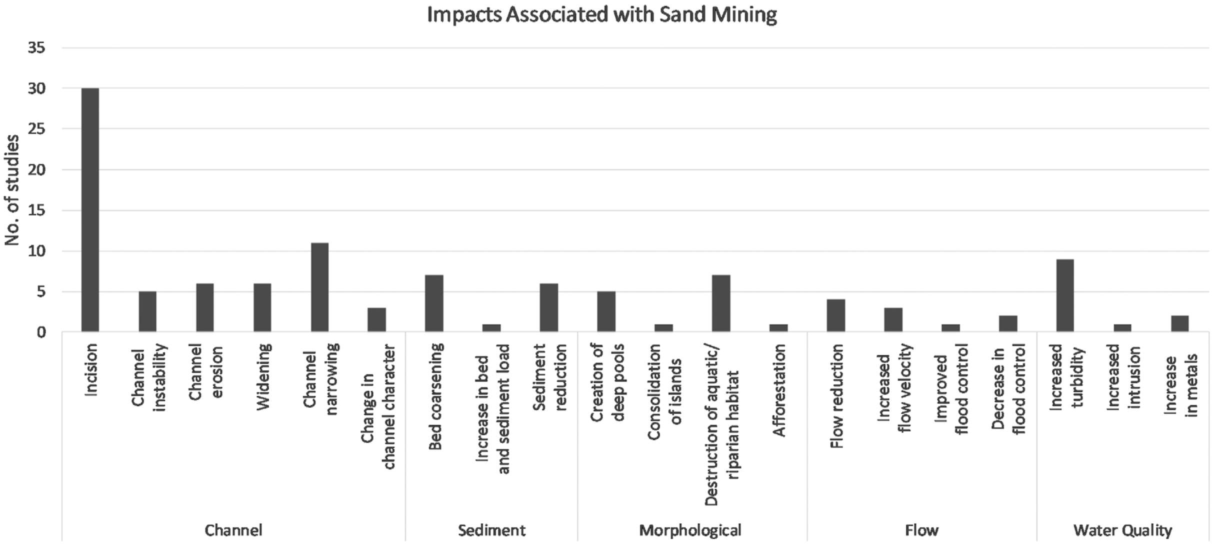

FIGURE 3 Summary of the physical impacts associated with sand mining identified in the structured Quick Scoping Review analysis

increases in sediment transport (due to exposure and transport of fine-sediment during mining and changed channel hydraulics), flow increases or decreases, and increased or decreased flood control. These observations suggest that although sand mining is likely to induce channel incision, there are a range of, often site-specific, physical impacts arising from sand mining.

The degree of channel incision ranged considerably, from 0.5 to 3.5 m (Dang, Umeda, & Yuhi, 2014), up to 10 m (Calle, Alho, & Benito, 2017; Skalski et al., 2016; Moretto et al., 2014; Gumiero, Rinaldi, Belletti, Lenzi, & Puppi, 2015) to over 30 m in the Bachang River in Taiwan (Huang, Liao, Pan, & Cheng, 2014). Substantial channel incision was generally associated with channel narrowing linked to bank erosion due to over steepening and destabilization of banks (Ortega-Becerril, Garzón, Béjar-Pizarro, & Martínez-Díaz, 2016; Campana et al., 2014). The extreme case of 30 m incision was accompanied by the channel narrowing to 1/6 of its original width. The widths of several rivers in the Piedmont and Tuscany regions of Italy have decreased by over 50% as a result of incision (Surian & Rinaldi, 2002). In a delta setting, thalweg deepening of about 1.5 m and irregular deepening was documented over a 10-year period in the Mekong (Brunier, Anthony, Goichot, Provansal, & Dussouillez, 2014).

In conjunction with other catchment activities, sand mining was found to be responsible for a change in the frequency and morphology of levees along the banks of the Hungarian Maros River, leading to the gradual disconnection of the river from its floodplain (Kiss, Balogh, Fiala, & Sipos, 2018). Incision was also linked to bar scalping or skimming mining methods, with the removal of the coarser armoured layer exposing underlying finer grained sediments that are more susceptible to erosion. Removal of bars was found to alter the hydrodynamic regime of the river and had significant knock on effects on the riverine and riparian environments (Kondolf, 1993).

The upstream progression of nick points was documented, with 11 km propagation documented by Kondolf (1997) and 12 km by Isik et al. (2008). These studies also reported channel widening, suggesting that substrates that are susceptible to upstream propagation of disturbances were also susceptible to lateral erosion processes. Incision and channel widening were associated with increasing the braiding of gravel bed rivers on the Ozark Plateau in central United States (Brown, Lyttle, & Brown, 1998). However, the opposite response was observed in rivers in southern France, where a decrease in braiding occurred following sand mining, although other catchment activities such as dams were identified as contributing to the changes (Liébault, Lallias-Tacon, Cassel, & Talaska, 2013).

Other channel changes associated with incision included thalweg relocation (Meador & Layher, 1998), decreased floodplain connectivity (Kiss et al., 2018; Wyżga et al., 2009; González, Masip, & Tabacchi, 2016), a reduction in connectivity between river and groundwater (González et al., 2016), and changes to groundwater levels (Bayram et al. 2014). Lower groundwater levels were linked to inhibiting the establishment of riparian vegetation on river banks impacted by sand mining in the lower Eygues River, France (Kondolf, Piégay, & Landon, 2007) and were suggested as hindering efforts to restore impacted rivers. Reduction in the water table level may also impact off-channel wetlands and tributaries and alter the seasonal flow regimes of rivers (Neal, 2009). Groundwater abstraction and associated ground subsidence combined with sand mining was identified as a driver of channel incision in the Nogalte stream, southeast Spain (Ortega-Becerril et al., 2016). Increased salt water intrusion was also a response to channel incision, with increased intrusion reported in the Kaluganga estuary in Sri Lanka (Ratnayake, Silva, & Kumara, 2013), the Tweed River in Australia (Rinaldi, Wyżga, & Surian, 2005), and in the Mekong (Brunier et al., 2014).

A loss of wetland area was linked to sand mining in a salt marsh in the Potomac River estuary, USA, with 55% of the surface area of the wetlands lost (Litwin et al., 2013). Erosion accelerated following the cessation of mining and was attributed to increased flooding and wave action on the highly altered coastal landscape.

Sand mining was found to affect sediment transport and the composition of riverbeds, including both reduced (González et al., 2016; Mingist & Gebremedhin, 2016; Kondolf, 1997; Podimata & Yannopoulos, 2016) and increased sediment loads (Sadeghi & Kheirfam, 2015). The selective removal of specific size fractions altered grain-size distributions in rivers (Mingist & Gebremedhin, 2016) and changed the bed load to sediment load ratio (Sadeghi & Kheirfam, 2015). Fine sediments mobilized by mining were found to accumulate in hydraulically quiescent locations, thus changing the distribution of riverine habitats (Freedman, Carline, & Stauffer, 2013).

The creation, deepening, and widening of pools were documented in Poyang Lake, China, with the changes being a major driver of increased discharge and reductions in the magnitude and duration of lake levels (Lai et al., 2014). These changes pose a risk to the extensive wetlands that are renowned for their biodiversity and provide vital habitat for half a million birds, including the critically endangered Siberian Crane (Lai et al., 2014).

3.3 | Impacts on riverine vegetation

The impacts of sand mining also extend to riparian zones. The creation of access roads and storage sites to support sand mining have fragmented riparian forests in the Lower Eygues River, France (Kondolf et al., 2007). The lowering of the water table caused by sand mining related incision may also prevent the establishment of pioneer forest on previously cleared riparian habitats (Kondolf et al., 2007). Gumiero et al. (2015) linked observed vegetation types (e.g., mature *Potametea* and *Charetea fragilis*) with particular landforms (e.g., channels) and found that the landform specific relationship with vegetation diminished in highly impacted river sections. Reaches that had undergone narrowing due to sand mining induced incision were colonized by a range of pioneer vegetation species and had higher plant species diversities compared with the least impacted river sections that exhibited the least diversity in community composition (Gumiero et al., 2015). Incision was also linked to the stabilization of riverine islands and an increase in riparian forests (Picco et al., 2012).

Asaeda and Sanjaya (2017) investigated the impacts of incision and aggradation on the colonization of steep, gravelly river reaches by riparian vegetation. They found that deposited gravel layers contained little moisture and nutrients and delayed colonization, whereas in river sections where the gravel layers are removed by mining, the establishment of riparian vegetation was accelerated. Kanehl and Lyons (1992) reported changes and a decrease in cover of in aquatic plant communities associated with increased scouring, decreased light penetration, and changing substrate compositions associated with sand mining.

Kumar and Kumar (2014) conducted a phytosociological study of a riverine sand mine and its surrounding areas in Palri Bhoptan village, Rajasthan, India. The primary impact was the direct removal of vegetation; however, the mining and dumping of tailings also altered soil profiles, changed the area's hydrology and topography, and altered the nutrient concentrations of the substrate. The changes in vegetation altered the rates of carbon and nitrogen cycling, the productivity of the ecosystem, and the structure of the microbial community.

3.4 | Impacts of water quality changes on invertebrates

Increased turbidity was linked to both instream mining and bar scalping (Kondolf, 1993). Béjar et al. (2017) found that suspended sediment concentrations associated with sand extraction could be similar to those occurring during peak flow periods and had differing effects on different groups of macroinvertebrates. Kanehl and Lyons (1992) reported a decrease in invertebrate populations resulting from direct removal during mining activities, habitat disruption, and increased sedimentation. Changes in turbidity were found to affect drift, compromise the ability of macroinvertebrates to colonize new river sections, escape suboptimal habitats and avoid intraspecific competition (Brittain & Eikelan, 1988), and alter the availability of invertebrates as a food source (Allan, 1978; Brittain & Eikelan, 1988). Fine sediments were also found to infill bed materials, changing rugose sediment surfaces to indurated and embedded substrate leading to a dramatic decrease in the macroinvertebrate taxa diversity and density (Duan et al. 2008). The removal of sand and gravel and the associated agitation of fine sediments in navigational pools in the Allegheny River, Pennsylvania, resulted in a decline and loss of communities within the freshwater mussel fauna and fish communities (Smith & Meyer, 2010).

Brown et al. (1998) found that impacts on macroinvertebrate assemblages varied between invertebrates of different sizes, and the magnitude and frequency of mining, with the density of large (*Corydalidae*, crayfish, and molluscs) and small invertebrates significantly higher in unmined sites, and a decrease in biomass of large invertebrates in mined reaches. Functional group analysis revealed that the abundance of collector–gatherers was unchanged between mined and unmined sites, whereas the number of collector–filterers decreased substantially. In an experiment removing limited sediment from a river, Rempel and Church (2009) found that mining temporarily changed the abundance and diversity of invertebrates; however, the mined section was immediately recolonized and returned to premined condition after a flood event.

Studies of sand mining in the Amite River, Lousiana, USA (Brown & Daniel, 2014) found increased risk of stranding and death for the Heelsplitter mussel (*Potamilus inflatus*) due to low water levels associated with incision. Skalski et al. (2016) investigated the effects of incision on the structure of ground beetle assemblages in riparian settings. They found the population structure of beetles was impacted on the lowest lying riparian reaches and linked this to clearing of riparian zones for agriculture as well as sand mining impacts.

Channel widening associated with bar scalping was linked to increases in water temperature where river velocities are low (Kondolf, 1993). These changes can reduce the availability of shelter and habitat for riverine species, whereas higher temperatures also result in lower dissolved oxygen concentrations and increases in the toxicity of pollutants such as heavy metals, insecticides, and natural toxicants (Heugens et al., 2001).

Impacts associated with the extraction and washing of material from the Harsit River in Turkey were found to include increased temperature and turbidity and higher manganese, chromium, and iron concentrations, with the increase in metals correlated with the suspended solids (Bayram & Önsoy, 2015). The study highlighted the potential for groundwater impacts that could affect domestic water use. The agitation and subsequent embedding of substrates were also linked to the spread of pollutants throughout river systems, with Nasrabadi et al. (2016) attributing homogeneous heavy metal concentrations in the Haraz basin in Iran to intensive sand mining activities.

3.5 | Impacts on fish

Physical changes to habitat availability and structure have been associated with direct and indirect impacts on fish (Kanehl & Lyons, 1992). The destruction of spawning grounds and interference to migration routes by mining were linked to a severe decline in local fish populations on the Arno-Garno and Ribb rivers in Ethiopia (Mingist & Gebremedhin, 2016). The removal of riffle sequences from riffle-pool controlled gravel rivers due to mining and incision lead to the replacement of lotic species by lentic species and allowed generalist and invasive species to displace native habitat specialists (Brown et al., 1998; Freedman et al., 2013 and Harvey & Lisle, 1998). The shifts were attributed to changes in river hydraulics caused by channel widening, with other stressors, such as dams, also contributing (Paukert, Schloesser, Fischer, & Eitzmann, 2011). A decrease in the diversity and abundance of fish was also linked to changes in river hydraulics between multichannelled unmined river reaches and single-channel incised reaches in the Czarny Dunajec River in the Polish Carpathians (Wyżga et al., 2009). The diversity and abundance of fish species increased linearly with increasing variation in depth within the multichannelled cross sections, and exponentially with improving hydromorphological river quality, as defined by European Standards, but were not linked to habitat area. The marked impoverishment of fish communities was attributed to the simplification of flow pattern and degradation of hydromorphological quality arising from sand mining. In Alaska, Meador and Layher (1998) linked the elimination of local fish populations with severe channel alterations associated with sand mining but did not suggest a mechanism for the decline.

Sand mining has also been linked to the destruction of spawning habitats by selectively removing sediments of a specific size that are used to construct spawning redds or nests (Harvey & Lisle, 1998; Kanehl & Lyons, 1992; Kondolf, 1993). Similarly, the rearrangement of benthic sediments during mining can hamper fish reproduction by decreasing the stability of the sediment deposits and impacting embryos sheltering within them (Harvey & Lisle, 1998). The replacement of rugose substrate by well-embedded fine-grained substrates had a greater impact on reproductive guilds requiring coarse substrates for nesting compared with nest or open spawner guilds that can burrow into the fine sediments (Freedman et al., 2013). In addition to damaging spawning habitats, fine sediments directly impacted silt-sensitive fish species (Brown et al., 1998).

Different mining methods have been linked to distinct impacts on fish. Suction mining was found to have the most impact on embryonic stages of fish, with juvenile and adult fishes more likely to avoid or survive passage through a suction dredge (Harvey & Lisle, 1998). Rempel and Church (2009) found that dry experimental bar scalping in the Fraser River, Canada, had no discernible impact on the local fish community. They concluded that the disturbance used in the study (extraction of 69,000 m^3) fell within the range naturally experienced by native organisms during flood events. Their results suggest that sand mining may have limited ecological impacts if controlled volumes are extracted at low frequencies using selective methods.

Meador and Layher (1998) found that although there was some variation between species, turbidity of less than 25 ppm did not harm fisheries, whereas chronic exposure to between 25 and 100 ppm could generally be tolerated. Higher levels had marked negative impacts, with sight feeders such as trout and bass more likely to be harmed than nonsight feeders such as catfish.

The effect of sand mining on groundwater levels has also been linked to impacts on fish populations. Warm summer river temperatures drive poikilothermic fish to seek cold water plumes created by groundwater seeps. Through lowering the water table, sand mining can reduce the intensity of these seeps, therefore removing these thermal refugia (Kurylyk et al., 2015).

Using stable isotope analysis of $\partial^{13}C$ and $\partial^{15}N$, Freedman et al. (2013) revealed that fish from undredged sites obtained nutrients from the benthos, whereas fish in dredged areas relied on phytoplankton and terrestrial detritus and occupied lower trophic positions, indicating that sand mining changed the food web structure. Similar impacts in food web structure were reported for Big Rib River, Wisconsin by Kanehl and Lyons (1992).

3.6 | Synthesis and recommendations

The QSR results demonstrate that the response of river ecosystems to sand mining is complex, with no one simple cause–effect model applicable to all systems. Channel incision is the most common physical change, but other responses are highly variable and linked to the inherent characteristics of the river system and other stressors. Collectively, the findings link sand mining to many changes in ecological structure, processes, and biodiversity of freshwater systems, including habitat loss and degradation, reduction and changes to the diversity and abundance of macroinvertebrate and fish populations, increased viability of invasive species, changes to food web dynamics, reductions in water quality and ground water levels, and alterations to riparian processes. Sustainable extraction based on limiting volumes to within the natural variability of a river's sediment load has been suggested (Rempel & Church, 2009), and geomorphology-based approaches to sustainable mining have been incorporated into voluntary Good Practice Guidelines in some regions (Department Irrigation and Drainage, Malaysia 2009), but there is no evidence in the scientific literature of sustainability on a commercial scale.

The documented response of rivers in the QSR review is unlikely to capture either the full scale or spectrum of impacts associated with sand mining. The geographic areas that have received the most research effort, rivers in temperate climates in North America and Europe, typically have stringent regulations and are not the areas where media articles describe extensive legal and illegal mining with few controls, areas which include China, India, Southeast Asia, Indonesia, Malaysia, and Bangladesh. Rivers in the rapidly developing economies of Asia and Africa urgently require research to quantify the rapidly accelerating pressures and their impacts associated with urbanization, hydropower, and other activities, so that science-based policies can be formulated. A first step would be the mapping and accurate quantification of extracted volumes such that the activity could be understood in the context of other sediment and flow disruptors such as hydropower. There is also scope to analyse the potential effectiveness of measures to improve management of sand mining in these contexts, especially in light of recent policy developments such as the recognition of the legal rights of rivers in countries such as Bangladesh and New Zealand, in order to achieve a balance between economic, social, and environmental outcomes.

Investigations need to consider rivers on a basin scale recognizing the importance of maintaining sediment continuity (erosion, transportation, and deposition throughout the system) to underpin ecosystem processes and maintenance of deltas under threat from climate change. This must include consideration of the interactions between sand mining and other river uses, such as hydropower, and land use changes that alter water and sediment supply. Investigations could usefully draw on historical research and incorporate a decade to century scale understanding of river response to hydromorphological changes, including the delayed response to change due to the buffering effect provided by sediment deposits within river and coastal settings and the coexistence of geomorphic thresholds. Research priorities should include how different taxa, including amphibians, birds, and mammals, for which there is a lack of information, are affected by mining and identify mitigation and management approaches to reduce and mitigate impacts. The findings need to underpin and guide the development of methods to identify sustainable mining targets for different river types, such that management strategies and targets are broadly transferable to other similar systems.

This review has only considered biophysical impacts on river systems. The socioeconomic implications, positive, neutral, and negative, for riverine communities and other stakeholder groups need to be considered in defining sustainable mining regimes. Broader research needs include understanding how shifting flow and sediment runoff patterns due to climate change, combined with increased development and urbanization will affect sand mining as an economic activity, and environmental threat over the coming decades.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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