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Review

The environmental impacts of river sand mining

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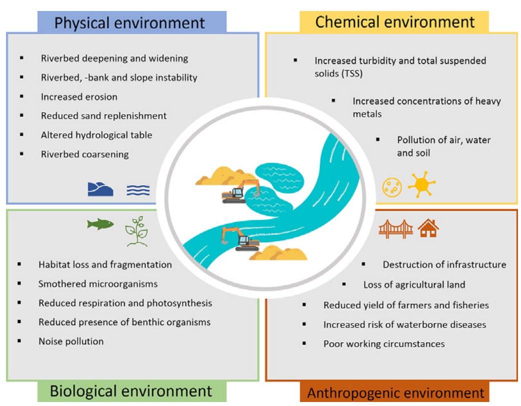
HIGHLIGHTS

- The increasing demand for construction-grade sand is a worldwide environmental issue.
- The type of extraction influences the magnitude of the impact on the environment.
- Effects are found on the physical, biological, chemical and anthropogenic environment.
- Effects are often widespread and cumulative and therefore hard to quantify.
- Development of science-based policies for sustainable mining should be prioritised.

GRAPHICAL ABSTRACT



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ABSTRACT

The demand for construction-grade sand is growing at a tremendous rate and the world is expected to run out of this resource by 2050. Construction-grade sand, hereafter referred to as 'sand', can be found in (former) aquatic environments, such as rivers and is a provisioning ecosystem service. Even under controlled circumstances, the practice of extracting the sand from the riverbed and -banks impacts the environment. Unfortunately, many countries lack sand mining regulation policies and in combination with a high demand, this results in indiscriminate and illegal mining. To create effective policies for sustainable extraction of river sand, there is a need for both qualitative and quantitative data on the effects of river sand mining. This paper brings together the effects of river sand mining on the physical, biological, chemical, and anthropogenic environment through a systematic literature review. The effects found are widespread and often cumulative. In the physical environment, the primary effects are riverbed widening and lowering. In the biological environment, the overarching effect is a reduced biodiversity and stretches from the aquatic and shoreline flora and fauna to the whole floodplain area. The effects on the chemical environment are a reduced water, air and soil quality through pollution. The effects on the anthropogenic environment comprise of damaged infrastructure, bad working circumstances for workers, limited access to water and agricultural losses. The findings of this research emphasize the complexity and cascading nature of the effects of river sand mining, as well as the severity and urgency of the problem. Based on the effects found and the four environments, a set of guidelines are proposed at the end of this paper to be used for global agenda making regarding sustainable sand extraction. Future research should prioritise quantifying the observed effects and developing science-based policies for sustainable mining.

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Contents

1. A global environmental crisis

After water, sand is the most consumed natural resource in the world. It has come to a point where sand is called "the new gold" and the indiscriminate extraction of this new gold is destroying physical and biological environments all over the world (Barton N. and Mini G., 2013). Sand is a provisioning ecosystem service and often extracted from aquatic environments, such as rivers and coasts. This is because water is an important means of transportation for sediment. The primary use of sand is for construction, since concrete consists for 75% of sand. This adds up to roughly 200 tons of sand for a house, 30.000 tons for every kilometre highway and a staggering 12 million tons of sand for a nuclear power plant (Ludacer, 2018). This huge demand for sand has caused the practice of sand mining to become a worldwide environmental issue (Asabonga et al., 2016).

Even though it would be in nature's best interest, a worldwide ban on sand mining is not an option as the demand for sand is enormous and ever-growing (Gallagher and Peduzzi, 2019). Between 1900 and 2010 the global demand for sand increased 23-fold (Torres et al., 2017) and it is expected to grow to a colossal 82 billion tons by 2060 (Fritts, 2019). Currently, around 50 billion tons of sand is used annually and that is already double the amount of sand that is produced by nature in that same time period (Ludacer, 2018). It takes the earth thousands of years to replenish the sediment stocks that are currently being overexploited. Recent calculations show that at the current extraction rate, the world could be running out of sand as early as 2050 (Sverdrup et al., 2017).

The largest demand for sand currently comes from China, which also hosts the largest urban area in the world. In just a couple of years, China has used more cement than the United States has in the entire twentieth century (Beiser, 2017). Lake Poyang has become the prime supplier of sand for China and is consequently the biggest sand mine in the world. Annually, around 236 million cubic metres of sand is extracted from the lake (Lai et al., 2014). The extraction, however, comes at a high cost for the environment. Lake Puyong is just one of many examples all over the world that illustrate the destructive impact sand mining activities have on the environment (e.g. in India (Bhattacharya et al., 2019), Nigeria (Akanwa, 2021), United States of America (Meador and Layher, 1998) and Hungary (Kiss et al., 2018)).

Mining itself already leads to drastic changes in the environment, but without proper legislation and regulation, the effects can be catastrophic. The extraction of one ecosystem service may lead to a decline in availability of several other services. The United Nations Environment Programme (UNEP) and World Wildlife Fund (WWF) have recently published reports on the problems surrounding river sand mining and they call attention to the fact that there is too few data, and a substantial lack of policies supporting responsible extraction and consumption of river sand (Gallagher and Peduzzi, 2019; Koehnken and Rintoul, 2018). In order to successfully implement sustainable policies, appropriate data on the extent of the dilemma is needed. The aim of this paper is therefore to give an overview of the environmental impact of river sand mining and this will be done by looking at the effects on the physical, biological, chemical and anthropogenic environment. Bringing together the effects on these environments will provide a novel overview which can be used as a guideline for global agenda making on sustainable sand extraction. Knowing which effects may occur is crucial in understanding how to prevent or mitigate said effects. After a brief theoretical background, the results will be discussed per environment. The methodology of the systematic review can be found as supplementary material. The results are discussed in the conclusion and recommendation section at the end of this paper.

2. The origin of sand

To assess the impact of river sand mining on the environment it is necessary to understand the underlying processes of sediment supply, transport and deposition. Sand might seem like an abundant resource, after all, our deserts appear to be filled with it. Unfortunately, sand that has been subject to wind-erosion (such as desert sand) is rounded and therefore less suitable for construction purposes. Construction-grade sand must be angular and should have a certain mineral composition. Hence the particular interest in river sand, which has a wide range of particle sizes and mineral properties (Padmalal et al., 2008). To improve the readability of this paper, the word "sand" is used consistently to refer to "construction-grade sand".

2.1. Sediment supply

The geographic location of the river and the river's origin for a large part determine the characteristic properties of the sediment. The dominant sources of sediment in a river catchment produce different types of sediment. Factors such as parent material, soil type and geomorphology of the landscape determine the mineralogical composition, grain size, durability and the quantity and quality of sediments (Collins and Dunne, 1990). These sediment sources, however, are exhaustive and need time to replenish (if they can). The main processes that are responsible for sediment delivery into the river can be identified in three categories: (1) mass wasting processes, (2) erosion of hillslopes by water and (3) erosion by rivers of their beds and banks Collins1990.

2.2. Sediment transport

The process of transporting eroded materials from the upstream highlands to the downstream lowlands is referred to as the "conveyor belt effect" by (Kondolf, 1997). Once the sediment is delivered to the river it can be transported as suspended or bed load. Suspended load includes fine-grained particles that are held in suspension in the stream and will only be deposited if the flow velocity is (near) zero. Bed load refers to coarser materials that are rolling, sliding, bouncing and/or being dragged along the streambed by traction or saltation (Christopherson, 2013). The latter, saltation, is the primary mean of transport of sand grains. Bagnold's

(1973) paper on the nature of saltation and bed load transport in water demonstrates the complexity of bed load transport. He states that, among others, depth and flow velocity are two important variables affecting the river's ability to transport sediment. A deeper riverbed or steeper slope could mean a higher discharge and an increased ability to transport sediment.

The systems at work are so complex that there is large uncertainty in our understanding of sediment transport. Generally, it can be assumed that the higher the flow velocity, the larger the particles the river can transport. During transport, the load is reduced in size through mechanical erosion such as abrasion (Barman et al., 2019b; Christopherson, 2013; Collins and Dunne, 1990). This means that the further away the sediment is transported, the more eroded the grains become and the less suitable for cement it will be.

2.3. Sediment deposition

The further the sediment is transported, the more abrasion the grains have been subjected to and the more eroded the grains are. Because the flow velocity and sediment carrying capacity of the water are correlated, the reduction of the gradient is often accompanied by a reduction of the grain size and increased sorting of grains (Collins and Dunne, 1990). In other words, the more downstream along the longitudinal stream profile of a river, the higher the percentage of fine particles (e.g. sand) is and the lower the percentage of coarse particles (e.g. gravel) is (Padmalal et al., 2008).

This phenomenon is the crux of river sand mining. Extraction companies want to find that sweet spot where the grain size and composition is ideal. Too far upstream and a lot of time and money will be spend on sorting out sediment, but too far downstream and the grains could be too rounded or have the wrong mineralogical composition. On top of this, sand is expensive to transport due to its weight. Mining is therefore preferably done close to where the sand is needed to prevent costs from soaring.

3. River sand mining

River sand mining is the extraction of sand (and gravel) from the drainage network of a river. By its nature, this practice effects the environment. The severity, however, depends on the rate, type and execution of the extraction. When the extraction rate is higher than the rate of natural replenishment, problems arise (Hackney et al., 2020). The type of extraction also influences the magnitude of the impact on the environment. Lastly, if the execution is not done in a sustainable and responsible way, the severity of the impact increases. Generally, two sources of river sediment are recognised: active channels and floodplain terraces and five types of mining:

1. channel wide instream mining
2. wet pit excavation
3. dry pit excavation
4. bar excavation
5. bar skimming

The first type is also the most destructive one as it comprises the extraction of sand from the entire active channel during the dry season (Padmalal and Maya, 2014). Pit excavation is rather straightforward as is it the extraction of sand from the riverbed or floodplain, causing a pit to form. If the sand is extracted from an active channel below the water table it is called wet pit mining. A common approach is to extract the sand using big machinery with suction pumps to suck up the sand and gravel (Padmalal et al., 2008). If the sand is extracted from the active channel of a dry or ephemeral river bed, it is called dry pit mining. In this case, digging is done using excavators, scrapers or manually by local workers (Padmalal and Maya, 2014). Bar skimming is a slightly more controlled way of extracting sand as they remove it from the top of exposed sand bars. Since these bars are above the water table it is possible to stay within a safe distance from the active water channel (Sreebha and Padmalal, 2011). Bar excavation is executed at the downstream end of a sand bar. Often, mining of the active channels takes place first before expanding to the surrounding floodplains and terraces (Padmalal and Maya, 2014).

The effects of these types of river sand mining are widespread and vary for each case study. However, they all affect either one or a combination of the physical, biological, chemical or anthropogenic environment. Therefore, the studied effects are classified into four categories based on the environment they affect most.

4. Effects on the physical environment

Indiscriminate river sand mining directly influences the shape of the riverbed. This often results in many indirect and cumulative effects on the physical characteristics and the dynamic equilibrium of erosion and sedimentation of a river. First, we look at the changes along the longitudinal subsection of a river. When sediment is extracted from the riverbed the sediment-supply balance tends to migrate upstream to compensate for the supply deficiency (De Leeuw et al., 2010; Knighton, 1984). When this happens, it causes increased erosion of the riverbed and -banks. Two main mechanisms intensify riverbed degradation: head cutting and 'hungry water'.

The excavation works create nick points which through the process of head cutting migrate upstream and generate even more sediment to be transported (Kondolf, 1997). This process is illustrated in Fig. 1. Ironically, the demobilized sediment is often delivered to the original site of sediment removal: the excavation site. Kondolf (1997, p.533) states the following about the hungry water mechanism: "If the continuity of sediment transport is interrupted by dams or removal of sediment from the channel by gravel mining, the flow may become sediment-starved". The transport capacity of running water is determined by the volume of water, the flow velocity and sediment load. The more sediment the river is carrying, the less energy is left for erosion. If the river deposits (part of) its sediment, the river will have more energy left for erosion. In the case of river mining, the sediment is deposited in the pits after the nick point and the water will erode downstream (Barman et al., 2019a; Kondolf, 1997; Padmalal and Maya, 2014).

When looking at the changes along the cross-sectional area of a river, pit excavation and bar skimming cause the riverbed to become respectively deeper and wider. Bar skimming and bank failure due to undercutting are the main factors contributing to the widening of the riverbed (De Leeuw et al., 2010; Erskine, 2008; Lai et al., 2014). Another way the riverbed is widened is by pit capturing. When wet pit mining is performed close to the active river channel, the wall of sediment separating the pit from the channel can collapse during high-flow regimes (Haghnazar and Saneie,

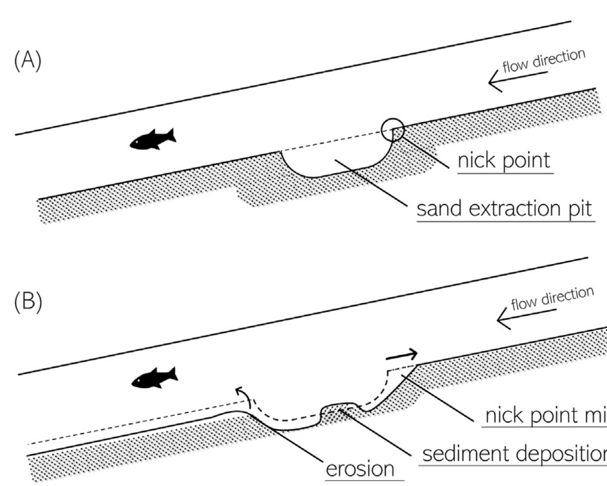

Fig. 1. Schematic representation of an incision produced by instream sand mining. a) Sand extraction creates a nick point; b) The nick point migrates upstream and the hungry water emerging from the deposition of sediments in the excavation pit erodes the bed downstream (modified after Kondolf, 1997).

2019). A quantitative assessment in the Mekong river by Hackney et al. (2020) showed that excessive sand mining induces river bed lowering, which can readily lead to river bank instability and increase the likelihood of a dangerous river bank collapse. Lai et al. (2014) conducted research on the effects of river sand mining in the area of Puyon Lake, China and found significant channel profile changes between 1998 and 2013 at three different cross-sections along the Hukou waterway, shown in Fig. 2. At all three cross-sections (a, b and c) the riverbed has become deeper and wider.

Presuming the inflow of water stays the same, the flow velocity reduces and could lead to even more sediment deposition in the excavation area when a riverbed becomes deeper and/or wider. A deeper and wider riverbed can also influence the groundwater table. A lower water table in the river causes a lower (ground)water table in the surrounding area. This, in turn, can cause a wide range of other problems. It could, for example, prevent recharge of a stratigraphically high aquifer (Padmalal and Maya, 2014). There have been many reports, from various regions across the globe (e.g. India (Padmalal et al., 2008), Iran (Zolghadr et al., 2021), Nigeria (Ako et al., 2014), Australia (Stow and Chang, 1987)), where the riverbed morphology was altered due to sand mining activities and where this induced hydrological changes which affected the low-flow regime of rivers.

Lastly, river sand mining induces some significant changes in sediment characteristics. A case study by Anooja et al. (2011) revealed that a change in the grain size spectral image was observed after indiscriminate mining activities. Padmalal et al. (2010) conclude the same for a river in Southwest India and also observed river bed coarsening due to the continuous removal of fine grains from the upstream area. Padmalal and Maya (2014, p.36) state that: “Point bars once composed entirely of sand-sized particles turn to gravelly sand and sandy gravel due to selective entrainment and removal of medium to very fine sands from the sediment population”. It can be concluded that persistent sand removal amplifies the natural process of sediment transport and sorting. Sand mining causes fine sands from upstream to be deposited in the downstream area. The lack of sufficient sediment might enhance the effect of sediment-deprived water during periods of high flow (Kondolf, 1997; Padmalal and Maya, 2014). The effects of river sand mining can also be seen at the coast where the lack of sand replenishment can cause beaches and dunes to erode faster and therewith offer less protection against storm surges, tsunamis and sea level rise (Shaghude et al., 2012).

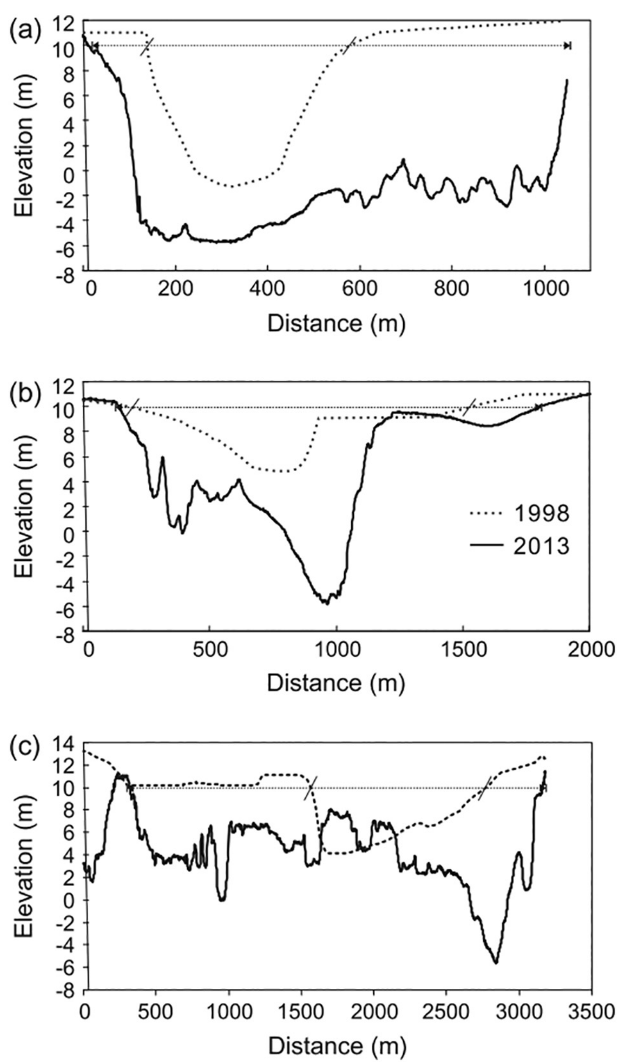

Fig. 2. Channel profile changes at three different cross-sections along the Hukou Waterway. From cross-section (a) to (b) to (c) the direction is upstream from the Yangtze river to Poyang Lake. Reprinted from Lai et al. (2014).

5. Effects on the biological environment

The effects of river sand mining extend beyond the immediate mining sites. Zou et al. (2019) state that: “knowledge of the effects of sand mining on freshwater lake ecosystems remains limited, especially for biotic communities”. Padmalal and Maya (2014, p.41) also state that: ‘relatively little attention has so far been made to unravel the effects of sand mining on the riverine biota’. The effects are so widespread and cumulative that the full extent of the impacts of river sand mining is not yet known. However, the effects that have been observed so far all show that river sand mining is degrading the biological environment and can have cascading effects on the entire food chain and ecosystem services (Torres et al., 2017). The general effects will be discussed in this section, but keep in mind that there are many more specific effects on the biological ecosystem possible and that they may vary for each case.

A stable riverbed is one of the conditions that ensures the (long-term) survival of many species. The sand layer on the solid riverbed is a hospitable environment for many microorganisms. Removal of the sand means instability and a loss of habitat for these organisms (Zou et al., 2019). Aquatic vegetation and microorganisms play an important role in maintaining the balance and health of the river's biological environment and when the balance in this ecosystem is disturbed it can be pushed to or crossed over a tipping point (Padmalal and Maya, 2014).

The extraction of sand stirs up the water and increases turbidity. This, in turn, blocks sunlight and reduces respiration and photosynthesis, but can also block respiratory organs of aquatic animals (Barman et al., 2019a; Padmalal and Maya, 2014). When deposited, the stirred up particles like silt and clay form a blanket on the river bed which can smother microorganisms such as diatoms, macroinvertebrates, benthic algae or fish eggs (Barman et al., 2019a; Padmalal and Maya, 2014). Sunilkumar (2002) studied the average abundance of benthic organisms in the Achonkovil river, India. Fig. 3 shows that there are significantly fewer benthic organisms in the disturbed area than there are in the undisturbed area. Similar results were found in the South Bengal river, India, by Bhattacharya et al. (2019). The widening of the riverbed can result in a shallow stream bed which often results in braided river flow. This type of flow hinders the movement of fishes between flows and pools (Lawal, 2011). De Leeuw et al. (2010) studied the effects of sand mining in Puyong lake, China and stated that the echolocation of the red-listed finless porpoise may be affected by dredging induced noise. Mazumder et al. (2014) conclude in their research that river sand mining threatened the Ganges river dolphin to the verge of extinction. These are no exceptional cases unfortunately and they can be seen in many environments that have been degraded by river sand mining.

The aforementioned changes in the biological environment have consequences for the entire food web. Zou et al. (2019) concluded in their research on the catastrophic effects of sand mining on macroinvertebrates that sand mining had indeed induced a substantial decline of macroinvertebrates. These organisms are at the bottom of the food chain

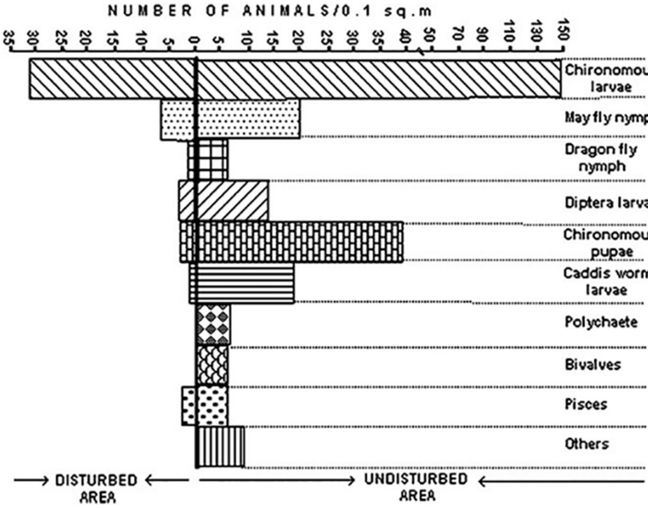

Fig. 3. Average abundance (0.1 m2 area) of benthic organisms in the Achankovil river. The number of animals per square meters is given for the disturbed area (left) and the undisturbed area (right). Reprinted from Sunilkumar (2002).

and the repercussions of such a decline can be felt many trophic levels higher, for example for humans who consume fish that feed on these macroinvertebrates. Also many terrestrial animals such as insects that feed of the aquatic life will be affected (Padmalal and Maya, 2014). The disturbed ecosystem balance can even favour invasive species.

Apart from the fauna, the mining also takes its toll on the flora. A direct way the flora is impacted is through the destruction of vegetation by means of bar skimming and transport-related infrastructure. This not only destroys the habitats above ground, but also below ground. Loss of riparian vegetation can increase erosion of riverbanks and adjacent slopes and contribute to the loss of sediment. A lowering groundwater table, as mentioned in the previous section, can be responsible for killing vegetation along the river and in the floodplain wetlands (Lawal, 2011; Sreebha and Padmalal, 2011). The riparian vegetation is an important factor for preserving the so-called 'Shaded Riverine Aquatic habitat' (SRA). The SRA comprises of overhead and instream vegetation cover providing, among others, shadow, bank stabilization and litter and thus a safe and nutrient-rich environment for many organisms (Padmalal and Maya, 2014). Destruction of this SRA is disastrous for the entire riverine environment.

6. Effects on the chemical environment

River sand mining does not alter the chemical properties of the sand but it does alter the local and downstream water quality. The extraction of sand from wet mining pits stirs up the water and induces cloud forming of fine organic and inorganic particles (Barman et al., 2019b). These particulate sediments carry nutrients and minerals which are normally transported downstream and discharged in marine environments (Padmalal and Maya, 2014). By extracting sand from the river, nutrients that are bound to the sediment are removed and the stirred up particles are deposited on downstream sand bars (Babu and Sreebha, 2004). These sand bars are on itself not able to sustain vegetation, but with the fresh layer of minerals and nutrients, they can transform into a flourishing green floodplain (Babu and Sreebha, 2004). This happened for example along the Periyar river in India (Padmalal and Maya, 2014; Padmalal et al., 2008). These green sand bars might not seem harmful, but they visualize the removal of nutrients from the river and thus the reduction of nutrient supply from terrestrial environments to marine environments.

Both the water and air quality are severely degraded by fuel/oil spills and exhaust fumes respectively from the machinery that is used for excavation and transport. This pollution affects the aquatic life, plants, animals and humans (Lawal, 2011; Padmalal et al., 2008). River sands can contain contaminants, and especially finer sand can accumulate more toxic elements like Cd (Kim et al., 2020), and river sand can inherit contaminants from other activities upstream in the catchment, for instance, mining (e.g. (Miller et al., 2003)) or other anthropogenic activities including agriculture. As mined sand is used elsewhere, its potential contamination should be evaluated before its use (Singh et al., 2017).

Ako et al. (2014) conducted a qualitative study assessing the impact of sand and gravel mining in Luku, North central Nigeria. They found concentrations of heavy metals such as lead, nickel, arsenic, cadmium, silver, copper and mercury in soil samples taken from mined locations that were (too) high. Lekomo et al. (2021) performed a physio-chemical analysis on water samples taken from the Toutsang river in West-Cameroon and found that sand mining practices increased the levels of total suspended solids (TSS), turbidity, magnesium and iron above WHO standards (see Fig. 4). Akankali et al. (2017) found similar results for magnesium, iron, zinc and manganese in the Okoro Nsit stream in Nigeria.

7. Effects on the anthropogenic environment

The anthropogenic environment is the environment created by humans. This comprises, among others, infrastructure, culture, economy and communities. So in other words, this subsection attempts to answer the question: "what are the effects on the man-made environment?". The process of riverbed deepening and widening causes both a vertical and lateral instability of the riverbed. The increased erosion together with the degradation of riparian and aquatic vegetation can result in the undermining and collapse of buildings, roads, bridges and the exposure of buried pipelines (Lawal, 2011; Padmalal et al., 2008). It also impacts riparian land owners and residents. Wang et al. (2012) performed a risk analysis of slope instability of levees under river sand mining conditions and concluded that: "The slope stability is seriously threatened" (p. 340) and that: "The probability of instability risk nearly doubled after sand mining" (p.348) in a case study they did. Apart from bank failure and slope instability, losses of agricultural land can also increase due to the lowered groundwater table as the irrigation structures will no longer reach the water (Padmalal and Maya, 2014). This can then result in loss of productivity of the land. The effects of sand mining on the fish population are felt by the local fisheries. There have been many reports of loss of fisheries' productivity due to river sand mining (Lawal, 2011; Padmalal et al., 2008; Peduzzi, 2014).

Another important effect of river sand mining was pointed out by Prasad and Nair (2004) who carried out a case study in the Achankovil river basin in Kerala. They found that indiscriminate sand mining is the

Fig. 4. Polluted water due to sand harvesting is the only source of usable water for indoor and outdoor household purposes by habitants of the Toutsang locality. Reprinted from Lekomo et al. (2021).

major causative factor of drinking water problems in that area. Local inhabitants dug wells that used to be filled up with water during the high-flow season so that they would have a buffer in the low-flow season. However, with the decline of the riverbed, these wells are now dried up all year as the water no longer reaches sufficient height to fill up the wells (see Fig. 5). Padmalal et al. (2008) concluded the same was happening in the Manimala river. In addition to this, the quality of the water is severely decreased by sand mining activities. As discussed earlier, heavy metals are found in concentrations above the WHO standard. This poses a threat to all communities that use the water for drinking, cooking or irrigation. Ako et al. (2014) found that the pits created by sand mining activities collect and store stagnant water during the raining season, which then serve as breeding ground for pests, such as mosquitoes, and other water borne insects. Just like the deterioration of the water quality, this can impact the health and livelihood of people living in and around the area.

Finally, it is important to point out that the business of sand mining is often a disreputable one. As sand becomes increasingly scarce, the price per cubic metre goes up and the sand is subject of illegal mining and trade (Torres et al., 2017). Sand is, compared to other natural resources such as oil and coal, rather easy to access. It is a common-pool resource and hard to protect from illegal mining activities (Schandl et al., 2018). For example, less than 4% of the 80 million tons of sand that Singapore imported from Cambodia was documented (Lamb et al., 2019). In roughly seventy countries, illegal sand mining by the so-called 'Sand Mafia' is a common occurrence (Bendixen et al., 2019; Torres et al., 2017). Reportedly, hundreds of lives have been lost in conflicts over sand in countries such as India, Kenya and Nigeria (Bendixen et al., 2019). There have also been reports of drowning incidents as the deep excavation pits form a metaphorical minefield in the riverbed (Sengani and Zvarivadza, 2018; Shaji and Anilkuar, 2014). Dust particles in the air, caused by the machinery, can cause irritation of the lungs and mucus membrane. And the contaminated water is often consumed by the miners due to a lack of an alternative source for drinking water (Ako et al., 2014). One could say that the sand mining industry creates jobs, but the circumstances under which people have to work and the effects on the (local) environment and livelihood are detrimental.

8. Conclusion and recommendations

The effects of river sand mining extend far beyond the immediate mining sites. The effects on the physical- and biological environment are often cumulative and therefore hard to quantify and assess. However, the observed effects generally result in a decreased geo- and biodiversity. The effects on the chemical and anthropogenic environment illustrate how river sand mining also severely affects the livelihood of people depending on or living near the river and that it can do great social and economic harm. The complexity and cascading nature of the effects show the urgency and severity of the problem. Unfortunately, the biggest consuming countries often have poor infrastructure and poor governing bodies. Rapidly developing countries of Asia and Africa require science-based policies and active enforcement.

Fig. 5. Impact of sand mining on rural water supply schemes: a water intake structure in Manimala, India, is exposed due to river bed lowering Reprinted from Padmalal et al. (2008).

Humanity is heavily dependent on well-functioning ecosystems and a constant flow of ecosystem services from nature to society. The extraction of sand, a provisioning service, is shown to affect an entire network of ecosystem services and therewith the availability of numerous ecosystem service flows. Quantification of the effects, as well as mapping them, should be prioritised in future research (Koehnken and Rintoul, 2018). In addition, this review considered the impacts of river sand mining on the physical, biological, chemical and anthropogenic environment, but to move towards sustainable mining policies, political and economic effects as well as different stakeholder groups should be taken into consideration.

In the context of sustainable sand extraction, there are several things that can be done to minimise the impact of river sand mining on the physical, biological, chemical and anthropogenic environment and protect our ecosystem services. The following three focus points could be used as guidance for global agenda making. Examples of guidelines are given for each point:

1. Source: Sustainable sources of construction-grade sand must be sought. These sources must be passive so the extraction does not damage rivers. An example is the newly-available sand from the retreating ice-sheet in Greenland (Bendixen et al., 2019; Mouyen et al., 2018).

   (a) An inventory of the available sediment resources through sand auditing should be made prior to sanction of leases (Padmalal and Maya, 2014).
   (b) The distance between river mining sites should depend on the width and replenishment rate of the river (Padmalal and Maya, 2014).
2. Govern: Global guidelines on where and when sand extraction is and is not sustainable are needed as well as an international framework to regulate and control sand mining activities (Bendixen et al., 2019).

   (a) Safety zones should be marked when mining in the proximity of infrastructure such as bridges or embankment (Padmalal and Maya, 2014).
   (b) Mining should be done during periods of lowest biological activity and authorities should be attentive to spawning seasons and condition (Padmalal and Maya, 2014).
3. Monitor: A global program to find and keep track of sediment mining is mandatory. This can be realized with the help of remote sensing. It is even possible to remotely track the sediment discharge rates of rivers and thus monitor the natural variations of sand flux in the world's rivers (Bendixen et al., 2019; Mouyen et al., 2018).

   (a) A pre- and post mining baseline survey as well as monitoring of mining activities should be incorporated in policy guidelines (Padmalal and Maya, 2014).
   (b) Periodic biota surveys should be conducted before, during and after mining operations (Padmalal and Maya, 2014).

CRediT authorship contribution statement

E.S. Rentier: conceptualization, methodology, formal analysis, investigation, resources, data curation, writing - original, visualization.
L.H. Cammeraat: writing - review, supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.155877.

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