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Managing exploitation of freshwater species and aggregates to protect and restore freshwater biodiversity

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Abstract

For millennia humans have extracted biological and physical resources from the planet to sustain societies and enable the development of technology and infrastructure. Growth in the human population and changing consumption patterns have increased the human footprint on ecosystems and their biodiversity, including in fresh waters. Freshwater ecosystems and biodiversity face many threats and it is now widely accepted that we are in a biodiversity crisis. One means of protecting and restoring freshwater biodiversity is to better manage the exploitation of freshwater biota and aggregate resources (e.g., sand, gravel, and boulders). Here we outline the threats arising from such exploitation and identify response options to ensure that methods and levels of extraction are sustainable and allow recovery of over-exploited freshwater biodiversity and ecosystems. The guidance we provide will enable practitioners, policy-makers, and resource stewards to embrace effective, sustainable, and evidence-based approaches to resource extraction. Response options for managing species exploitation include strengthening assessment and reporting, using science-based approaches to reduce overexploitation and support recovery, embracing community engagement, and building or tightening legislation. Response options for managing exploitation of freshwater aggregate resources include reducing demand for harvest, strengthening governance, reporting, and monitoring of environmental impacts, and promoting the restoration of degraded ecosystems or compensating for losses. Diverse case studies highlight examples of where various management actions have been implemented in an effort to consider how they can be scaled up and adapted to other contexts. Managing exploitation will be a key aspect of broader initiatives needed to protect and restore freshwater biodiversity around the globe.

Key words: anthropocene, inland fisheries, sand and gravel mining, overexploitation, natural resources

Introduction

Humans have long depended on natural resources to sustain societies and enable the development of civilizations. Early hominids foraged plants and animals from lands and waters to provide nutrition and materials needed for clothing and other purposes. Physical resources, such as aggregates (e.g., sand and gravel), were harvested to enable the construction of buildings/shelters and infrastructure often using mortar and concrete often to the detriment of aquatic systems (Cooke et al. 2020). As the human population has grown, the processes of urbanization, industrialization, and globalization have dramatically increased the demand for, and extraction of, natural resources. By all accounts, much of contemporary resource extraction is at or near levels that are unsustainable (Sutherland and Reynolds 1998). Overexploitation (defined as the harvesting or extraction of renewable or non-renewable natural resources at levels that are unsustainable, such that they negatively impact physical and ecological processes and lead to population declines and biodiversity loss, including extirpation or extinction [see Mace and Reynolds 2001 for further discussion] or depletion of non-renewable resources) is now regarded as one of the primary threats to biodiversity and ecosystem stability (Rosser and Mainka 2002). From the collapse of the overharvested Chinese paddlefish population to the receding of the Mekong Delta due to sand mining and dams (Kondolf et al. 2022), examples of resource overexploitation are widespread (Chen et al. 2020). We recognize the importance of these sectors and industries for supporting livelihoods, food security, housing and transportation needs, and human well-being. However, continued use of these resources relies on healthy ecosystems (in the case of aquatic life), unaltered sediment dynamics (in terms of aggregates), and sustainable management. Overexploitation precludes their long-term use, impacting on future generations that depend on these resources.

Resource extraction is a global issue affecting all ecosystem types and fresh waters have been particularly impacted. Freshwater ecosystems are among the most degraded and imperiled on the planet as a result of diverse threats (Dudgeon et al. 2006; Reid et al. 2019; Arthington 2021). Correspondingly, freshwater biodiversity is in crisis (Harrison et al. 2018) with the WWF Living Planet Index revealing declines in over 80% of freshwater biota populations since the 1970s (WWF 2020). Indeed, the state of freshwater ecosystems and biodiversity is so dire that Tickner et al. (2020) created an "Emergency Recovery Plan" to protect and restore freshwater biodiversity. That plan includes six sets of actions, one of which is managing exploitation of freshwater species and aggregates in ways that are not only sustainable but that allow for biodiversity to be rebuilt. Recently, Twardek et al. (2021) advocated for more efforts to be devoted to implementation and rallying diverse actors to work together to implement the Emergency Action Plan. There have also been regional efforts that focus on adapting the recovery plan for a specific region (see Reid et al. 2022), and other calls to better engage and support practitioners in their important work (Cooke and Birnie-Gauvin 2022). The Emergency Recovery Plan was necessarily brief, so there is need to expand on the six actions and provide specific response measures that can be adopted and implemented.

To that end, this paper identifies the causes and recommends solutions to the problems of the harvest of biological resources and extraction of aggregates from freshwater systems. We first provide a brief overview of the threats arising from extraction of freshwater resources. We then focus on identifying response options for enhancing management so that resource exploitation is sustainable and allows for the maintenance and recovery of freshwater biodiversity. The proposed response options are supported by case studies documenting where they have already been used with some success. The case studies were selected in an attempt to provide examples from around the globe (in developed and developing countries) that span systems, issues, and taxa. The case studies are particularly enlightening in that on-the-ground success stories are not always captured in peer-reviewed papers. We then discuss implementation challenges and how they can potentially be overcome. Combined with other papers that will explore the other five Emergency Action Plan strategies (in Tickner et al. 2020), this practical exercise will equip practitioners, policy-makers, and resource stewards with the knowledge and impetus to implement the Emergency Action Plan and "bend the curve" of freshwater biodiversity loss (i.e., from declining to growing populations). Our team includes scientists and practitioners from around the globe that collectively engage in efforts to enhance the management of the exploitation of freshwater biota and aggregates to protect and restore freshwater biodiversity and support food security and livelihoods of people depending on this.

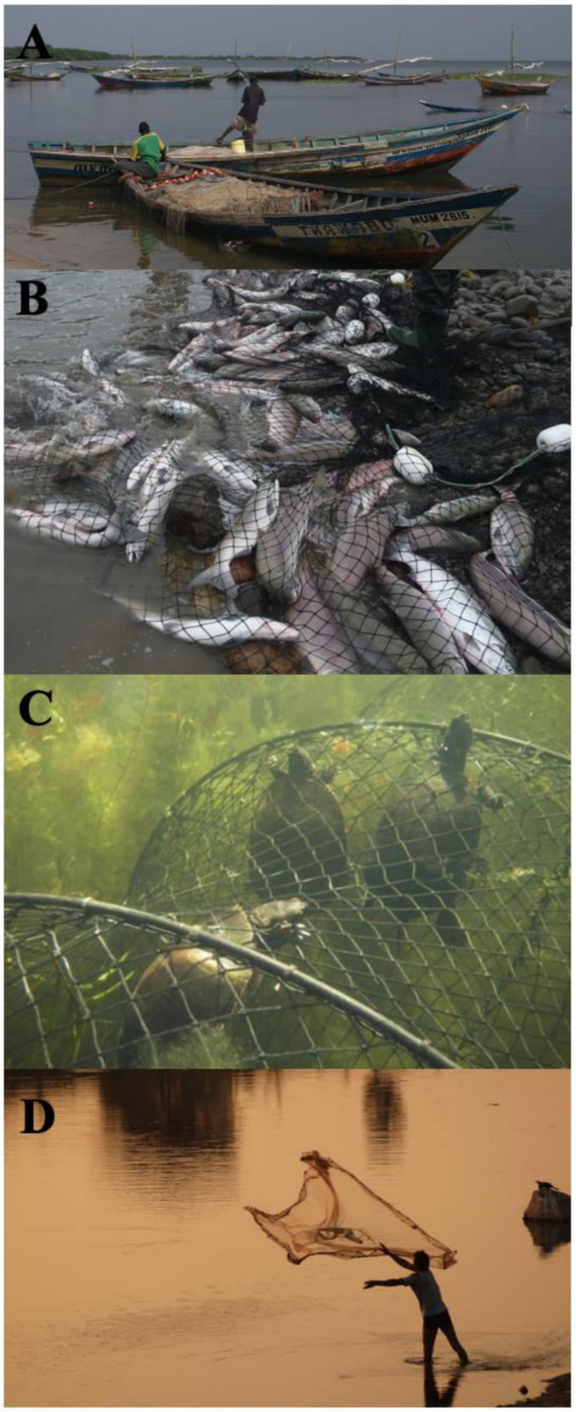
The issue

Widespread overexploitation of both biological (Dudgeon et al. 2006) and aggregate resources (UNEP 2019) has long been recognized as a substantial threat to freshwater biodiversity. Here we briefly summarize the nature of the problem, impacts on freshwater biodiversity, and the state of the science. Given the different contexts and practices for biological and aggregate exploitation, each is covered separately.

Biological resources

Freshwater ecosystems represent a relatively small percentage of the Earth's surface, while supporting over 10% of all species; these ecosystems also tend to be hotspots of anthropogenic activities (Strayer and Dudgeon 2010). Overexploitation of biological resources occurs for many taxa and comes in many different forms (Fig. 1; Dudgeon et al. 2006).

Fig. 1. Biological exploitation (harvest) comes in many forms. (A) Extensive fishing fleets exist on Lake Victoria in Africa where these have been concerns for decades about overfishing. Credit: Soaring Flamingo, CC BY-ND 2.0. (B) Pacific salmon face a number of threats including chronic overfishing in the Pacific northwest. Credit: Cooke Lab. (C) Threatened freshwater turtles are captured as bycatch during some finfish fisheries such as in eastern Ontario. Credit: Cooke Lab. (D) Nets are one of the forms of gears used in subsistence fisheries. Credit: Unsplash.



Organisms that are harvested (e.g., mostly fishes, reptiles, amphibians, invertebrates, and waterbirds) are typically extracted for food (Tregidgo et al. 2020), livelihoods, recreation (e.g., angling), or cultural services (see Lynch et al. 2016, 2023; Pelicice et al. 2023) and overexploitation can be due to heavy and/or indiscriminate harvesting, and/or incidental bycatch (Reid et al. 2019). For example, within North America, intensive harvesting of freshwater mussels (*Bivalvia* spp.) has led to annual yields and catch per unit effort declining dramatically over the past century and subsequent industry collapse (Anthony and Downing 2001). In the past several decades, unselective fishing has largely reduced fishery resources and homogenized fish assemblage structures in Chinese inland water bodies (Liu et al. 2022). During the 18th century, Portuguese settlers in Amazonia captured millions of the giant South American river turtle eggs for oil, which was used as fuel to light houses and streets (Santos and Fiori 2020). Unmanaged aquarium fisheries in Western Ghats of India have resulted in large-scale population declines, and subsequent endangered listing of endemic species (Raghavan et al. 2013). Relative to targeted or indiscriminate harvesting, overexploitation caused by incidental bycatch can impact an even wider variety of taxa: fishes, birds, reptiles, mammals, and invertebrates (Raby et al. 2011). Imperilled turtle species have been incidentally caught in small-scale commercial fisheries in Ontario Canada, and this bycatch was projected to eventually lead to the extirpation of the species (Midwood et al. 2015). In another case, mortality of river dolphins was documented in the Brazilian Amazon due to artisanal gillnet fisheries (Iriarte and Marmontel 2013). In some cases, freshwater organisms are harvested for bait (e.g., river dolphins used for bait in Amazonia; Serrano et al. 2007; small-bodied fish used for bait in North America; Litvak and Mandrak 1993). Broadly, overexploitation of biological resources has led to substantial declines of freshwater species abundances and range, leading to extirpation in some populations.

Since the growth of conservation biology as a discipline in the 1980s, there has been increased focus on protecting freshwater ecosystems and organisms (see Soule 1985), underpinned by substantial research to further our understanding of the impacts of overexploitation and to identify mitigation strategies. Despite this proliferation of research, there remain many unknowns and challenges regarding the full impacts of intensive harvest and overexploitation and selection of the best remedial approaches. There have been substantial efforts to assess the status of freshwater species at the international (e.g., the International Union for Conservation of Nature Red List of Threatened Species, or the WWF Living Planet Index) and national (Desforges et al. 2022) scales. Such assessments have yielded critical insights. For example, for close to 600 freshwater-dependent species assessed as threatened on the IUCN Red List, biological resource use, in the form of exploitation/harvest, has been flagged as a major threat (IUCN Red List 2022). However, most assessments are regional, taxon-specific, or use indicator species (rather than every species), and do not register collapses in populations. For example, Canada's recreational fisheries have undergone significant declines in recent decades that went unnoticed by fisheries scientists, managers, and the public (Post et al. 2002), and in China there has been collapse of fisheries in the Yangtze River (Mei et al. 2020). Without full assessment of status or understanding of threats, other freshwater species could also experience invisible collapses. While the Emergency Recovery plan (Tickner et al. 2020) could still be embraced and implemented to alleviate anthropogenic impacts on freshwater organisms, status assessments must contribute to understanding progress and efficacy of remedial efforts.

Aggregate resources

The overexploitation of aggregate resources has been recognized as a threat to biodiversity (Torres et al. 2021) and has recently garnered attention due to associated environmental impacts (Fig. 2). Rapid growth in human population, urbanization, and infrastructure development have led to increases in demand for construction materials (e.g., aggregate resources such as sand and gravel), which have become the world's most extracted solid materials by mass (OECD 2018). Freshwater systems, including rivers and lakes, are major sources of aggregates, which can be extracted from the bottom or exposed areas around the edges of waterbodies (Kowalska and Sobczyk 2014). As these deposits are easily accessible and are often close to or well communicated with human settlements, they are often targeted for mining (Torres et al. 2017). Aggregates are delivered by rivers from erosion upstream as part of sediment cycling through the landscape. However, large scale removal and exploitation of aggregate resources often exceed the replenishment rate and can alter the fluvial geomorphology of the waterway leading to habitat alteration and both direct (e.g., injuries and mortalities) and indirect (e.g., changes to substrate, increased turbidity, and altered hydraulics at catchment and even basin scales) impacts to already imperilled freshwater species (Chen et al. 2017). This problem is further exacerbated by the construction of large dams that trap sediments and thereby deprive downstream reaches of their natural sediment load.

There are many examples of serious impacts of aggregate extraction on freshwater ecosystems and biodiversity, for example, mining operations in the largest sand mine in the world located in Poyang Lake, China, has led to increased mortalities of critically endangered Yangtze finless porpoise (*Neophocaena asiaeorientalis asiaeorientalis*) via stranding caused by changes in water regimes (Li et al. 2022). In Dongting Lake, extensive mining activities and barges carrying the sand downstream have fragmented porpoise populations and even blocked river-lake movements (Han et al. 2023). The surfacing frequency of the endangered Gangetic river dolphin (*Platanista gangetica*) was three times longer than natural dive rates, and the acoustic activities of the species was reduced during mining and dredging days in the River Ganges (Kelkar 2016). The full extent of impacts of unsustainable aggregate exploitation goes far beyond the mining site and extends beyond just the riverbed and include water quality changes (e.g., increased turbidity), water regime alteration (e.g., changes to hydraulics which can occur at the catchment scale, but has potential to impact hydrology across the entire basin), habitat modification and/or destruction (e.g., erosion, wetland destruction, and nesting/spawning site loss; Koehnken et al. 2020), and increased noise and traffic. For example, destruction of spawning beds and blockage of migration routes via aggregate extraction in Ethiopia resulted in severe population reductions in multiple fish populations (Mingist and Gebremedhin 2016), impacting food security for nearby communities (Mensah 1997). There can also be indirect negative effects beyond the boundaries of freshwater systems. For example, in France, riparian zones were fragmented during the construction of access roads and storage sites for sand mining in a river (Kondolf et al. 2007). While aggregate extraction has been fully or partially restricted in rivers in many high-income countries over the last decades due to environmental and social concerns (Hámor and Kovács 2018; Torres et al. 2021), this activity is now rapidly expanding in many rivers in fast-growing regions and is largely unregulated, poorly monitored or even illegal (Koehnken and Rintoul 2018; Magliocca et al. 2021).

Although the extraction of aggregates from fresh waters has been reported to have severe impacts, there is a need for more reliable information and scientific inquiry (Koehnken and Rintoul 2018). There is limited evidence that exploiting aggregate deposits in unregulated rivers can be sustainable if the extracted volumes remain within the variability of the natural rate of sediment delivery, and the extraction is for a limited duration (Rempel and Church 2009). However, the processes, responses, and impacts are often nonlinear and difficult to quantify with excessive exploitation increasing the risk of cascading impacts (Schumm 1979). Scientific research focused on quantifying the magnitude and extent of indirect ecological impacts, and identifying management and remediation efforts to minimize and reverse negative effects on freshwater biodiversity, are urgently needed. Similar to the extraction of biological resources, the lack of status assessments for biota affected by the removal of aggregates, many of which might be still undescribed, is likely hindering management whereby populations could be unknowingly declining due to exploitation of aggregates (Torres et al. 2021). To date, most of the research on aggregate impacts has been in Western countries (North America and Europe) with stringent regulations; however, in rapidly emerging economic areas (e.g., across Africa and Asia), where demand is high and mining is often conducted informally or illegally, there is a severe paucity of studies regarding the full extent of aggregates extraction, methods employed, and magnitude of associated impacts (Koehnken et al. 2020). Such an assessment can be particularly challenging in basins prone to sediment trapping by large dams (Ran et al. 2013), or increased sediment yield from the landscape due to land use changes (Wilkinson et al. 2014). Efforts to define sustainable levels of aggregate extraction have been challenging. Another area that could benefit from further research is the refinement and development of spatial planning and sourcing approaches that look beyond mining sites to entire supply networks of aggregates (Torres et al. 2021), allowing to maximize material efficiency (e.g., recycled materials; UNEP 2019) and examine alternative supply streams (e.g., crushed rock) and their trade-offs to alleviate pressures on freshwater biodiversity.

Fig. 2. Extraction of aggregate resources occurs in lakes and rivers around the globe. (A) Sand extraction in the Mekong River in Lao PDR (Credit: Olivier Gilard, CC BY-NC 2.0). (B) Wooden canoes are used to transport gravel collected from the bed of the Goyain River in Bangladesh (CC BY 2.0).

Response options

When it comes to extraction/exploitation, it can be useful to consider the system beyond the actual harvesting. This can include all of the components/activities before and after harvesting, including drivers of exploitation, as well as the governance/management/policy interventions that apply to any of those arenas. For biological resources, we use the term “harvest”, whereas for aggregate resources we use the term “extraction”. We have organized the response options accordingly (Fig. 3), presenting them in a logical sequence that includes: (1) pre (harvest or extraction) response options; 2) extraction response options; and (3) post (harvest or extraction) response options (for summary see Table 1).

Biological

Pre-harvest

Response option 1: *Assess biological resources and fishing activities to inform management*

Fundamental to the sustainable management of biological resources is an understanding of the state of the resources, which will require inclusion of knowledge from diverse sources. Basic information such as species assemblage

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Fig. 3. Conceptual diagram of the three phases of harvest or extraction for biological and aggregate resources highlighting the response options.

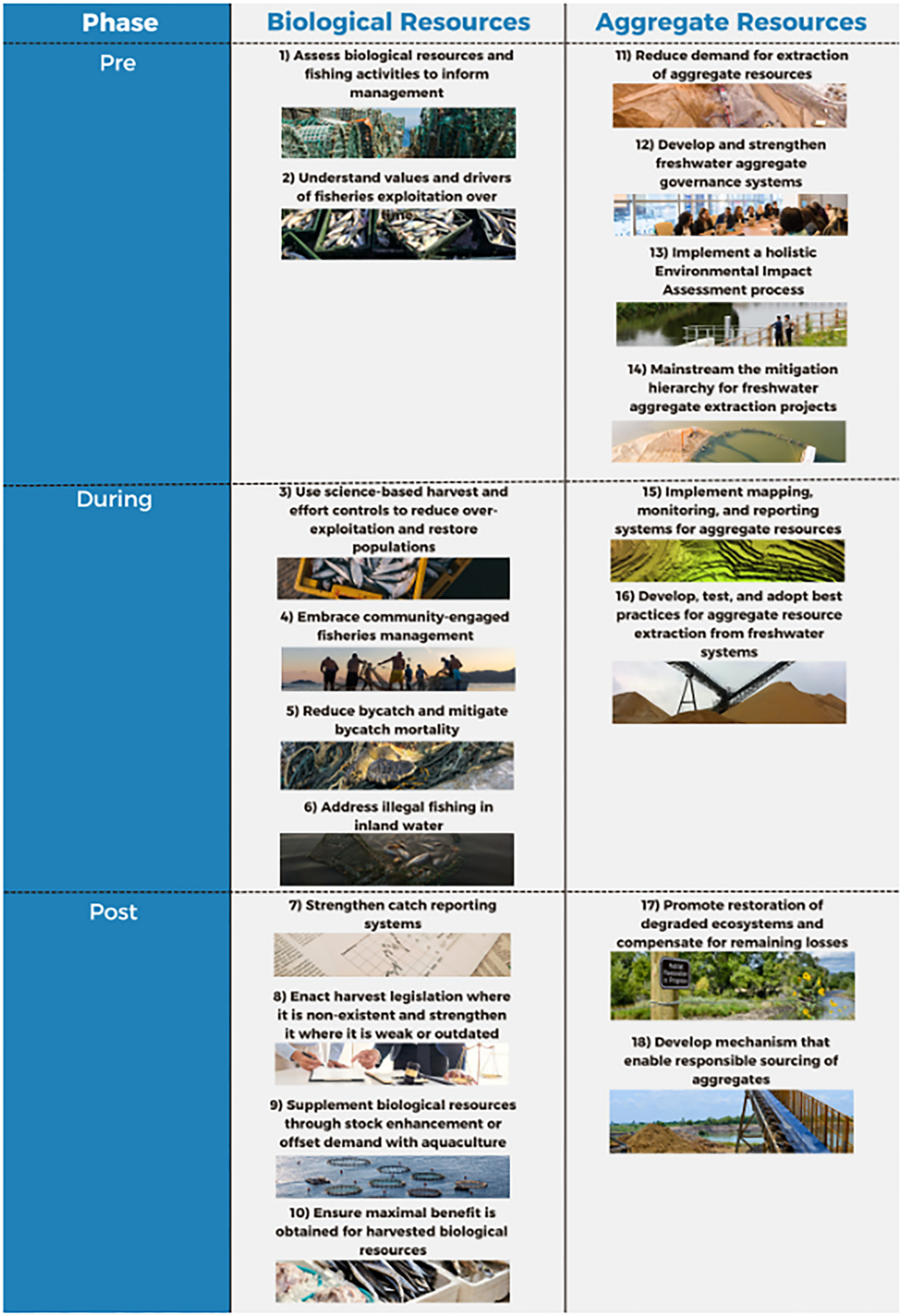

Table 1. Summary of response options for managing exploitation of freshwater species and aggregates according to resource type and harvest or extraction phase.

Resource type	Phase	Response option
Biological	Pre-harvest	***1.*** *Assess biological resources and fishing activities to inform management*
		2. *Understand values and drivers of fisheries exploitation over time*
	Harvest	***3.*** *Use science-based harvest and effort controls to reduce overexploitation and restore populations*
		4. *Embrace community-engaged fisheries management*
		5. *Reduce bycatch and mitigate bycatch mortality*
		6. *Address illegal fishing in inland water*
	Post-harvest	***7.*** *Strengthen catch reporting systems*
		8. *Enact harvest legislation where it is non-existent and strengthen it where it is weak or outdated*
		9. *Supplement biological resources through stock enhancement or offset demand with aquaculture*
		10. *Ensure maximal benefit is obtained from harvested biological resources*
Aggregates	Pre-extraction	***11.*** *Reduce demand for extraction of new aggregate resources*
		12. *Develop and strengthen freshwater aggregate governance systems*
		13. *Implement a holistic Environmental Impact Assessment process*
		14. *Mainstream the mitigation hierarchy for freshwater aggregate extraction projects*
	Extraction	***15.*** *Implement mapping, monitoring, and reporting systems for aggregate resources*
		16. *Develop, test, and adopt best practices for aggregate resource extraction from freshwater systems*
	Post-extraction	***17.*** *Promote restoration of degraded ecosystems and compensate for remaining losses*
		18. *Develop mechanisms that enable responsible sourcing of aggregates*

composition, biomass, and stock structure and vital rates (e.g., growth, maturity, and mortality) of key species is essential for establishing science-based fisheries management targets and management actions. Information on habitat condition and risks, such as water supply and water quality, is required to determine if the ecosystem is self-supporting or under threat as compound impacts (over-use of resources combined with habitat degradation) are a particularly high risk for freshwater species. Unfortunately, the majority of inland fisheries are data poor or lack the fundamental information on which to base patterns of exploitation (Cooke et al. 2016*b*). Nevertheless, valuable primary information about the fisheries can be obtained from local ecological knowledge and household and market surveys (e.g., Fluet-Chouinard et al. 2018). Information on the fisheries themselves is also needed—knowledge of the type of fishery, gears used, effort, fishing mortality, socioeconomic aspects, markets and distribution of catches, and historical and current management regulations all provide critical insights to addressing overexploitation. It should also be recognised that the majority of inland fisheries do not occur in a vacuum—it is generally external threats and natural variation in environmental factors (e.g., hydrology and nutrients) that influence productivity and hence yield (Welcomme et al. 2010). Thus, an understanding of the externalities and environmental drivers is necessary. Assessment is not a separate entity but rather an integral component of the fisheries assessment–management cycle that relies on continuous monitoring and adjustment (King 2013). There are many inland fisheries and fish populations for which overexploitation is not a problem (Allan et al. 2005), so knowing where there are problems (or potential for problems to develop) can be used to guide management. Avoiding overexploitation in the first place is always preferable to having to try and apply remedies after fisheries collapse (Roughgarden and Smith 1996). Assessment of inland fisheries can be perceived as difficult, but there are proven assessment methods available to understand diversity, biomass and other metrics. There's also a growing number of new tools (some that rely on technology such as eDNA or hydroacoustics) that can be used (Lorenzen et al. 2016). There are also evolving tools for dealing with data-poor fisheries (Fitzgerald et al. 2018).

Response option 2: *Understand values and drivers of fisheries exploitation over time*

As environmental challenges mount in complexity, fisheries professionals must develop and practice holistic solutions to support sustainable harvest. Tackling current and future concerns requires knowledge of historical fishery usage, and the values and drivers of exploitation as they have changed over time. Many freshwater fisheries that were formerly exploited for subsistence purposes using traditional gears and governed by local rules have undergone massive change as fishing pressure gradually increased through human population growth, globalization, commodification, and privatization (Pitcher and Lam 2015). As fisheries became disconnected from local values (e.g., respectful relationships with local resources) and drivers (e.g., subsistence) toward post-industrial, capitalist structures (e.g., utilitarianism and profit maximization), communities have been marginalized and traditional values, local knowledge, and long-established approaches to management have eroded (Noble et al. 2016; Berenji 2020). This can result in a lack of recognition about the importance of fisheries for providing essential nutrition (protein and micro-nutrients) which is extremely difficult to replace by simply converting to other food systems. Local, historical knowledge is essential for accurately establishing baselines to reveal the true extent of historic change in fisheries resources to avoid management decisions that are based on skewed or shifted perceptions of the state of environmental degradation (Christensen and Tull 2014). Such knowledge is critical when understanding how to best manage degraded freshwater ecosystems and preserve biodiversity (Berkes et al. 2000; Noble et al. 2016). It is also important to assess the different types of fisheries and their value chains to understand the nature of over-extraction in each context. For example, management approaches will differ for intensive, large commercial enterprises extracting for high value markets (e.g., trout or salmon harvesting in North America and tambaqui or Arapaima in Amazon) versus widely dispersed, subsistence-oriented fisheries (e.g., artisanal fisheries in the lower Mekong and Amazon basins; Tregidgo et al. 2017, 2021). One must also consider differences in values and drivers among recreational, commercial, and subsistence sectors. In most industrialized countries, recreational fishing is already the dominant source of exploitation in freshwater ecosystems (Cooke et al. 2016*b*), and this sector is growing in low- and middle-income countries (Bower et al. 2020). Management for the recreational sector requires alternative approaches to commercial or subsistence fisheries considering the diverse values and motivations for engaging in recreational fishing (Cooke et al. 2018; Nyboer et al. 2022). Understanding changes in patterns of fishery exploitation over time can also shed light on whose needs are being met by fishery policies and practices, and different regulations and enforcement, so that efforts to limit extraction do not harm poor, disenfranchised, or marginalized people terms of livelihoods, food security, and culture (Christensen and Tull 2014; Berenji 2020; Whelan et al. 2020).

Case study: Integrated approach to addressing overexploitation within the Lower Mekong Basin of Southeast Asia

The Lower Mekong Basin (LMB) is one of the world's largest and most productive inland fisheries (MRC 2019). More than 2.3 million tonnes of fish, valued at an estimated $11 billion, are harvested annually from the LMB (So et al. 2015). Fisheries exploitation has occurred since early in the history of the region and especially during colonial periods when fisheries became more organized, driven by food demand and population growth. Intense fishing pressure in Viet Nam and Cambodia became prominent in the 1950s but occurred later in Lao PDR. Fishing pressure also increased with improved access through infrastructural development (roads) and the availability of modern fishing gears (e.g., nylon gill nets) at affordable prices. These fisheries are also under considerable pressure from rapid economic development, especially agriculture, hydropower, industrial expansion and mining, and a growing human population (MRC 2019; Vu et al. 2021). Consequently, several previously important fishery species in the LMB have declined significantly and are now considered Critically Endangered. These include Jullien's golden carp (*Probarbus jullieni*), giant barb (*Catlocarpio siamensis*), and giant pangasius (*Pangasius sanitwongsei;* Poulsen et al. 2004).

A number of approaches have been implemented to reduce pressure on the fisheries, most notably the use of classical fisheries management input-output regulations such as gear restrictions, closed areas, and seasons, although there have been difficulties enforcing these regulations in most fisheries (especially the diffuse ones). Some of these measures are orientated around cultural norms that have been in place for centuries. More recently, protected areas and fish conservation zones have been introduced across the LMB to protect key fish habitats, and habitat restoration measures to reconnect important floodplain habitats are in their infancy (Baird 2006; Baumgartner et al. 2021). Finally, large scale stocking of key species of economic importance is prominent across all countries of the LMB to support fisheries, an action that is recognised by national fish stocking days (Cowx et al. 2015).

Case study: Regulating the aquarium trade in India

Increasing demand for tropical freshwater fishes as aquarium pets has triggered large-scale collection of endemic and threatened species, including from India's biodiversity hotspots. Although native fish species from the country were first exported to England in the 1930s, commercial-scale exports evolved only in the late 1990s, which subsequently led to the indiscriminate collection of endemic and threatened species (Raghavan et al. 2013). For example, on average around 50 000 individuals of two endangered species, redline torpedo barb (*Sahyadria denisonii*) and zebra loach (*Botia striata*), are wild-caught and exported every year (Raghavan et al. 2013; Tapkir et al. 2021). As an open-access, unmanaged, and unregulated fishery, a characteristic "boom-and-bust" pattern has been evident, with many local populations subjected to intensive overexploitation within short time spans (Raghavan et al. 2018; Harrington et al. 2022). In response to this emerging conservation challenge, several regional- and national-level strategies and action plans have been developed and implemented for certain species. This includes the setting of a minimum legal size at harvest to restrict collection of immature juveniles, catch-quotas, and seasonal closures of the fishery for *S. denisonii*, and promoting their captive breeding. In August 2022, *Channa barca*, a popular snakehead that fetches US$1000/piece was included in the Indian Wildlife Protection Act, the first time a freshwater fish has been listed since the inception of the Act in 1972.

Harvest

Response option 3: *Use science-based harvest and effort controls to reduce overexploitation and restore populations*

A vast science-based toolbox exists for managing biological resources in ways that either regulate overexploitation or enable the restoration of depleted (or even extirpated) populations, although most of the practical applications are specific to a handful of finfish with high socio-economic value (e.g., salmonids, percids, and cichlids). The use of such tools implies that there is a functional assessment programme interfaced with governance structures that enables management or enforcement. In many inland waters, especially in low-income countries, one or both of those key elements is often missing. Gear restrictions focused on different types of gears (e.g., limits on mesh size and banning of explosives and piscicides) or on when, where, or how they can be deployed are common tools for protecting freshwater biodiversity. Effort controls can also be used, often through spatial closures (e.g., protected areas and sanctuaries) or by limited entry fisheries where only a certain number of licences, boats, or gears are permitted. Although widely used, these tools do not work in all situations and are often applied on a species-specific basis rather than in a holistic manner (i.e., ecosystem-based). In some cases, interventions are applied in systems where there is no evidence of their effectiveness, or where the ecosystem-level consequences are poorly understood (Cowx and Gerdeaux 2004). Adaptive management is thus necessary to ensure that there are learning opportunities so that management efforts can be adjusted as necessary (Marttunen and Vehanen 2004). Reconciling efforts focused on single species with an ecosystem approach provides opportunity to consider and manage complex interactions and is increasingly being embraced in inland waters (Beard et al. 2011), such as the Amazon basin (Goulding et al. 2019).

Response option 4: *Embrace community-engaged fisheries management*

Overexploitation of biological resources through fisheries can be mitigated through community-based management (CBM) and resource protection that involves engaging with local communities. Nearly 20% of the global land area is designated for or owned by Indigenous Peoples and local communities (Rights and Resources Initiative 2015) and recent evidence has shown that Indigenous-managed lands have biodiversity levels comparable to protected areas (Schuster et al. 2019). Community-engaged approaches include the involvement of local resource users (i.e., fishers and anglers), in decision-making and management (Johannes et al. 2000). Engagement within the community can take many forms such as co-development of management objectives, monitoring, developing and enforcing rules and regulations, participating in research, sanctioning, advocacy, promoting, and/or driving conservation, and participation in fisheries planning (Granek et al. 2008). CBM can empower local users who may have been previously marginalized and disenfranchised, especially if there is a true shift in authority toward local communities and adequate provision of economic capacity to carry out management activities (Jentoft 2005; Nunan et al. 2018). Such activities are, however, severely compromised if there are no incentives for the local communities to engage and implement management activities.

Case study: Community-engaged fisheries management in northwestern Thailand

While similar practices are widespread throughout Southeast Asia, one well-documented story of community-engaged fisheries management comes from the ethnic Karen communities of the Mae Ngao (Ngao River) in northwestern Thailand. In response to declines in fish catch due to both local overexploitation and the use of illegal fishing methods like electricity and dynamite introduced by outsiders, these communities have created a network of over 50 no-take fish reserves throughout the river basin. Communities have adopted additional management actions that include gear prohibitions; complete bans on electrofishing and the use of explosives, and some have further prohibited the use of diving masks, which also facilitated overharvest of fish and other aquatic organisms (e.g., snails, frogs, turtles, aquatic insects, and plants; Duker and Klanarongchao 2022). Initial guidance from a local non-governmental organization prompted one community, Mae Lui, to implement a 900 m long no-take fish reserve in the early 1990s. Upon seeing the successful increase of large fishes from the riverbank, nearby communities slowly adopted the practice. In the last 10 years, due in large part to improved road access to upstream communities, the number of reserves has surpassed 50 communities, which together protect nearly 2% of the perennial river length basin-wide. Despite the relatively low percentage under protection, reserves (identified by community members based on local knowledge and so are not randomly selected) were found to harbor 27% higher fish richness, 124% higher density of fish, and 2247% higher fish biomass than adjacent fished areas (Koning et al. 2020). Furthermore, reserve assemblages were shown to support important ecosystem processes through maintained trophic interactions (Koning and McIntyre 2021). Astoundingly, these benefits are realized despite a lack of formal recognition or support from the Thai government and little coordination among communities themselves. Still, community members credit their collective actions for sustaining fish diversity to their ongoing harvests and food security (Duker and Klanarongchao 2022).

Case study: Combating freshwater turtle egg harvest in the Brazilian Amazon with community-engaged management

Human expansion has affected wildlife species across Amazonian waterways and is likely to increase pressure as it continues to grow even in the most remote areas. Amapá State, in the eastern Brazilian Amazon, has an extensive network of protected areas, which represents about 74% of the total area of the state (Michalski et al. 2020). However, population growth in Amapá has been increasing rapidly, with a population of 669 526 people in 2010 projected to nearly double to 1 312 240 by 2060 (IBGE 2022). Thus, exploitation of yellow-spotted river turtles (*Podocnemis unifilis*) is likely to increase. For example, in a survey with 51 riverine residents around a sustainable-use reserve in Amapá state, 59% of the respondents reported that they had eaten *Podocnemis unifilis* eggs during the previous year, which equated to an approximately total of 1602 eggs eaten annually along 105 km of river (Norris and Michalski 2013). In a study, on a 33 km stretch of river that runs between two sustainable-use reserves in Amapá state, enforcement patrols with four to six government officials checking for illegal activities around protected areas had no effect on *Podocnemis unifilis* nest harvesting, while community-engaged management approaches dropped nests harvest levels nearly threefold to a rate (26%) that is likely sufficient for river turtle population recovery (Norris et al. 2018). The community-engaged management activities were focused on landowners who participated in nest protection activities around strategic larger nesting areas (Norris et al. 2018). The findings from the community-engaged management in Amapá state were overwhelmingly positive and illustrate that a focus on community involvement can generate benefits for conservation along waterways.

 Environ. Rev. **32:** 414–437 (2024) | dx.doi.org/10.1139/er-2022-0118

Case study: Achieving sustainable Arapaima fisheries in the Brazilian Amazon basin through community-based management

Community management of Arapaima, locally know as pirarucu, fisheries has been considered one of the best examples of the success of such a response option. The pirarucu, one of the largest freshwater species (up to 3 m long), has historically been one of the main fisheries resources in the Amazon (Castello and Stewart 2010). Most of its landings are illegal, disregarding both minimum catch sizes and closed seasons (Cavole et al. 2015). Because overexploitation has led to declines in wild populations (Castello and Stewart 2010), the pirarucu is among the fishes of greatest conservation concern (Allan et al. 2005). However, community-engaged fisheries management initiatives (e.g., collectively agreed upon harvest regulations) have been shown to be efficient in recovering its small-scale fishery in Brazil. For example, the species' population and respective catches increased 10-fold in less than a decade of management with the participation of fishers, at the Mamirauá Sustainable Development Reserve (Castello et al. 2009). The management system has been widely disseminated with significant growth in managed areas and number of fishers involved (McGrath et al. 2015).

Response option 5: *Reduce bycatch and mitigate bycatch mortality*

Bycatch occurs when non-target species are encountered during fishing operations. Bycatch is well known in marine commercial fisheries but also occurs in inland waters in both commercial (including bait harvest) and recreational fisheries (Raby et al. 2011). In most food insecure regions, the term "bycatch" is misleading because essentially anything that is caught is utilised for food or feed products, and efforts to make fisheries more selective could impact food security. A first step in addressing freshwater bycatch is to acknowledge it as a potential issue and characterize the extent of the problem. Doing so would identify specific fisheries for which there is need for targeted research and management actions that yield solutions that will be embraced by fishers. Modifications in gear (e.g., to make fisheries more selective) or to include exclusion devices are common. Exclusion devices have been used in crustacean traps to reduce platypus bycatch in Australia (Serena et al. 2016), and otter exclusion devices are used on fyke nets (Koed and Deperink 2001), while in British Columbia restrictions on seine net length have been used to reduce catch so that endangered coho salmon bycatch can be found and released more quickly (Raby et al. 2015). Attempts to use temporal or spatial fishing restrictions to reduce bycatch can also be effective but have rarely been applied in fresh waters (Drake and Mandrak 2014), and these measures are largely aimed at protecting species of high conservation value. In the recreational sector, catch-and-release is common in both a voluntary and regulatory context and there have been many efforts focused on developing strategies to minimize stress and injury, and maximize survival of released fish (Brownscombe et al. 2017). What is clear is that fisher values, perspectives, and knowledge will ultimately influence the extent to which they will engage in behaviours that reduce bycatch. As such, working closely with fishers (as occurs frequently in the marine realm; Barz et al. 2020) is essential for developing, refining, and implementing solutions that will be embraced voluntarily or yield high levels of compliance with regulatory actions.

Case study: Mitigation strategies for freshwater turtle bycatch in small-scale fisheries, Ontario, Canada

Various freshwater turtle species (most are listed provincially under the *Species at Risk Act*) are encountered in small-scale commercial hoop net fisheries targeting finfish in lakes of eastern Ontario, Canada. Turtles drown in nets when they are submerged for extended periods of time and are unable to access the surface to breathe. Very low levels of adult turtle mortality can result in localized extirpation given the life-history of turtles (i.e., late age at maturation; Midwood et al. 2015). Focused research has identified strategies for reducing bycatch of turtles, as well as keeping turtles alive while in the nets. Efforts to use exclusion devices (see Cairns et al. 2013) failed to adequately restrict entry of some of the smaller-bodied turtles, reduced fish catch, and made net tending more difficult, suggesting challenges with implementation. However, providing simple air spaces (e.g., using an inflatable beach ball in the net) was sufficient to keep turtles alive (Larocque et al. 2012). Given that mortality of turtles is temperature-dependent, mandated net checks that varied by water temperature (i.e., more frequent at warmer temperatures) provided added protection. Human dimensions research focused on commercial fishers revealed that there was a need to educate them on why turtles, which several decades ago could be legally harvested, were now subject to protection (Nguyen et al. 2013). Such efforts might increase compliance with regulations. Identifying the prevalence and consequences of turtle bycatch and testing various solutions provided resource managers with feasible solutions, and the impetus to change regulations both locally and in other regions (Larocque et al. 2020).

Response option 6: *Address illegal fishing in inland water*

Illegal fishing spans sectors and regions with inland examples becoming more common in recent years. Infractions can be minor (e.g., a recreational angler fishing without a licence) or more extreme (e.g., a sophisticated poaching ring linked to organized crime) but collectively can contribute to fisheries overexploitation, particularly if managers are unaware of the activity and thus unable to account for it in fisheries mortality estimates (Gigliotti and Taylor 1990). Although increasing enforcement efforts and raising associated penalties is often proposed as the most immediate solution to illegal fishing (via deterrence; Ehrlich 1972), the reality is that increasing policy compliance is complex and requires a nuanced understanding of social, cultural, and economic factors. Given that governance structures are highly variable with different levels of legislative support, enforcement, and corruption (which undermines legitimacy of management; Nunan et al. 2018), efforts that focus on education have the potential to be useful in some contexts. Broader public education and awareness campaigns as well as those targeted directly toward fishers about the impacts of unauthorized fishing can be powerful tools for adjusting social norms. Use of illegal gears is a common problem in inland fisheries, but there are a number of solutions available. First, when illegal gears are seized they should be destroyed to prevent them from re-entering service, and from an educational perspective, there is the possibility to provide advice on legal gears and even provide access or subsidies for legal fishing gears. Programmes that enable fishers to replace prohibited gears or otherwise compensate them have proved effective. In some cases, illegal gears can be banned from import, further reducing likelihood of illegal gear use. Co-management efforts, whereby resource users are more directly involved in decisions regarding a resource, have also been identified as a potential means of reducing illegal fishing (Etiegni et al. 2011; Song et al. 2020).

Case study: Addressing illegal, unreported, and unregulated fisheries in Lake Victoria, Africa

Illegal fishing has been rife in Lake Victoria, East Africa, since the explosion of the Nile perch fishery in the 1980s. It is occurring on the lake mainly through the ongoing use of undeclared or prohibited fishing gear (e.g., small-mesh monofilament gillnets, beach seines, and small hooks) (LVFO 2016; Daghar 2019). Early efforts to deter illegal fishing included confiscation of seine nest and small mesh gill nets in Kenya and Uganda and burning them in public to act as a deterrent. Since the early 2000s, Beach Management Units, a form of decentralized co-management structures, have been established with the aim to improve compliance with fisheries regulations (among other things). While initially successful at curbing some illegal fishing (Downing et al. 2014), co-management initiatives have not led to a noticeable reduction in illegal fishing in the long term due to inconsistent leadership, ongoing issues of corruption and bribery, and inadequate funding and power transfer from the top down (Nunan et al. 2018). More recently, Uganda and Kenya have reverted effort to publicly confiscate and burn illegal seine nets bringing back a top-down approach to governance and enforcement. Although anecdotal evidence indicates initial success of such initiatives with increased catches of some fish species, such practices undermine social cohesion and agency within communities in the long term (Nyboer et al. 2022). (Re)-involving local resource users in the management and enforcement remains an essential step towards encouraging and achieving sustainable practices (Luomba et al. 2016; Nunan et al. 2018). Learning from past shortfalls and successes of Lake Victoria co-management system is critical. The use of mobile courts around Lake Victoria is a recent innovation introduced by the Tanzanian government. It holds great potential as it can speed up the hearing and sentencing of illegal fishing cases as well as closing off corruption and the bribing of government officials (Daghar 2019). Finally, a concerted regional response will need to be pursued where the three countries' relevant departments—environment, fisheries and trade—meet to discuss fishing operations and collaborate on joint patrols (Nunan and Onyango 2017).

Post-harvest

Response option 7: *Strengthen catch reporting systems*

Knowledge of harvest (e.g., total catch—or proxies such as CPUE or catch assemblage) is an essential part of developing sustainable management plans (Hilborn and Walters 2013). Once biological resources are harvested, it is important to ensure that catches/harvests are adequately reported (Bartley et al. 2015). For decades, the harvest of freshwater biological resources has been poorly documented, which means that the value of these resources has been underreported (Cooke et al. 2016*a*; Fluet-Chouinard et al. 2018; Ainsworth et al. 2023). To that end, there is dire need to develop novel methods to estimate catches consistent with reporting requirements, including the use of traditional catch assessment surveys (Lorenzen et al. 2016), consumer and agriculture surveys (e.g., household surveys; Fluet-Chouinard et al. 2018), new technologies (e.g., smart phone reporting apps that are used by anglers on a routine basis; Venturelli et al. 2017), and implementing community monitoring approaches. Furthermore, it is necessary to improve and harmonize fisheries information and related data collection across regions and to aggregate such information at a national and global scale (as per De Graaf et al. 2015) to understand the value of freshwater biological resource harvest and how such resources support nutrition and livelihoods (Beard et al. 2011).

Response option 8: *Enact harvest legislation where it is nonexistent and strengthen it where it is weak or outdated*

Effective international, national, or regional policy is useful for guiding the development of management plans that ensure biological resources are not subject to overharvest. Although there are reasonably well-developed policies that deal with the harvest of marine biological resources, similar policies are less common for inland waters. In many instances, this is because the value of such resources is poorly recognised. Inland fisheries tend to be highly dispersed, small-scale and with many inland fisheries exploited for subsistence or as part-time livelihood activity. In addition, the development of policies that guide the sustainable management of inland biological resources can be complex because of the number of sectors, water users, and actors involved (e.g., hydropower and agriculture) that are competing with biological resources for water (Beard et al. 2011). As such, it can be convenient to simply ignore fisheries relative to these other water uses. However, this is problematic as if they are ignored they tend to be poorly managed and unreported, which is bad for freshwater ecosystems (given other threats plus the potential for overharvest), and bad for those that depend on the harvest of inland biological resources. There is urgent need to develop, review, and revise national and transboundary freshwater policies regional regulatory frameworks that explicitly include freshwater biological resources alongside other sectoral needs (Taylor and Bartley 2016; Song et al. 2018) and do so in ways that can be implemented at a watershed scale (Nguyen et al. 2016). However, those efforts need to be supported with compliance monitoring and enforcement.

Case study: Improving harvest legislation on freshwater fisheries in the Yangtze River and other Chinese river basins

According to the UN FAO, China is the largest producer of freshwater fish in the world with the Yangze being the fourth largest freshwater fish producer in the world. Historically, exploitation of fisheries resources in Chinese inland waters was poorly regulated and is one of the major drivers in declining freshwater biodiversity and loss of endangered species

(Chen et al. 2020), although pollution and habitat degradation are equally, if not more, responsible (Zhao et al. 2015; Kang et al. 2017). As a result, fishing in many inland waters, including the Yangtze River basin, has been banned. The fishing ban has evolved through a series of stages: spring spawning seasonal bans in certain river reaches, extending the ban period beyond the spawning season and into the regulated river reaches, and ultimately implementing a 10-year period fishing ban over the entire Yangtze River basin (Chen et al. 2020; Liu et al. 2022). This has had significant impact on more than 300,000 people who depend on fishing for their livelihoods, but is anticipated to improve stocks and halt loss of biodiversity (http://www.chinatoday.com.cn/ctenglish/2018/sl/202009/t20200930_800222421.html).

Response option 9: *Supplement biological resources through stock enhancement or offset demand with aquaculture*

When biological resources are depleted or to enhance populations to enable exploitation, organisms can be cultured in captivity and then introduced into freshwater systems (e.g., Welcomme et al. 1983; Cowx et al. 2015). This phenomenon is most widely known for fish where there are well-established hatchery systems. However, the evidence of positive impact of fishery enhancement is limited for both fishery and conservation purposes. Furthermore, introducing captive bred individuals into a wild population can introduce an additional stressor to an ecosystem, including competition and predation risk to wild fish from captive-bred fish, the risk of disease and parasite introductions into wild fish populations from captive populations, and genetic risk to wild populations which may result in inbreeding or outbreeding, with the result being reduced fitness of wild fish. We acknowledge that hatcheries themselves can be the basis for conservation problems so any supplementation must be done in a manner that is consistent with maintaining the biodiversity of endemic populations, and that all stock enhancement needs to be approached with caution to ensure that non-endemic species are not introduced (Cowx et al. 2015). Recent attempts to raise endangered freshwater fishes and molluscs have encountered challenges (Rytwinski et al. 2021) emphasizing that most effort to date has focused on socioeconomically valuable species. Any attempts to stock should be prefaced by other actions that first aim to address the basis for any declines, in particular addressing the bottlenecks to recruitment and habitat improvement measures (Welcomme et al. 2015). Another option is to offset demand using freshwater aquaculture. However, there is no guarantee that aquaculture produced fish (a potentially expensive commodity) will provide a direct replacement of a wild-capture fishery (a generally free commodity). Further, aquaculture can also threaten freshwater ecosystems (and their wild fisheries) through habitat destruction and alteration, and the introduction of invasive non-native species, so again, such efforts need to be done in ways that do not degrade ecosystem health or potentially risk native flora and fauna (Boyd et al. 2008; Devi et al. 2017; Nobile et al. 2020). The culture of inland aquatic products for nutrition or other uses, if carefully managed, is a potentially useful approach to provide alternatives that would reduce reliance on harvest of wild resources. A further consideration is ownership of stocked fish—does the replacement of a wild capture fishery with a stocked fishery or aquaculture result in reduced access to local people, if so, is the problem being displaced? Such questions must be answered before engaging in such efforts to ensure that additional biological or socio-economic issues are not created (see Arthur et al. 2022).

Response option 10: *Ensure maximal benefit is obtained from harvested biological resources*

Inland fisheries are incredibly important across the globe, as they support local economies, employment, and livelihoods and provide food security and a source of nutrition (Cooke et al. 2016*b*; Funge-Smith and Bennett 2019). Therefore, it is important to maximize the benefits generated from fisheries harvest to ensure that these resources are not wasted. Post-harvest fish losses or waste continues to persist (Makawa et al. 2019), and currently there is limited information to determine the extent of these occurrences in terms of magnitude, quantity, and quality (Chiwaula et al. 2020). For example, in Bangladesh, high post-harvest fish loss was mainly attributed to poor packaging and handling, as well as decreased efficiencies at collection points (Acharjee et al. 2021). Mitigation strategies aimed at reducing post harvest spoilage and maintaining product quality quantity include provision of icing or freezing facilities and training in better handling, linked with improving the market chain through more efficient transportation and infrastructure (Hodges et al. 2011; Acharjee et al. 2021). There are also opportunities to improve processing methods that prolong the shelf life and ensure that nutritional quality is maintained (Ghaly et al. 2010). These improvements to minimize waste would promote more sustainable livelihoods. In terms of food security and nutrition, another option to maximize value of harvest resources is to enhance the associated impact of resources that are already being extracted, for example by increasing access by nutritionally vulnerable populations, (e.g., through targeted investments in post-harvest distribution or promoting sale to school feeding programs (Bennett et al. 2022). Additionally, increasing the nutritional value of extracted resources can also maximize the value, and this can be achieved through the adaptation of fish value-added products or improved processing methods (Cooke et al. 2021).

Aggregates

Pre-extraction

Response option 11: *Reduce demand of aggregate resources*

Reducing demand of aggregates sourced from freshwater and overall natural systems is the most straightforward option for reducing mining impacts on biodiversity. Actions to reduce the demand of primary aggregates require efforts by developers, industry, and regulators. Fortunately, there have been some promising developments. Many processes linked with the flow of aggregates through the economy are inefficient or wasteful, creating plentiful opportunities for increasing material efficiency. For instance, construction and demolition waste is the heaviest and most voluminous solid waste fraction (35% of the solid waste produced worldwide; UNEP 2015). Adopting a more circular approach to aggregate use could yield manifold benefits in terms of reducing carbon footprint while increasing profit for commercial entities (Supino et al. 2016), albeit a number of research gaps remain (Wu et al. 2019). Technical and engineering solutions related to developing products that require less concrete (e.g., lightweight building designs), that use alternative products (e.g., industrial by-products as alternatives to fine aggregates in concrete; Santosh et al. 2021; use of copper mine waste rocks; Benahsina et al. 2022; reviewed in Kirthika et al. 2020) or that extend the lifetime of buildings and infrastructure (Hooton and Bickley 2014), reduce demand on further extraction. These secondary aggregates need to be tested to ensure that they do not cause more harm (e.g., pollution) and have the same strength, particularly is seismic areas. However, these technical improvements must be accompanied with strategies and societal efforts to reduce the material footprint per capita (IRP 2020) but that will require changing lifestyles and consumption patterns (Kostadinova 2016). To decrease demand, governments should underpin system-level changes through incentives and policies. National and state-level policy and legal instruments influence production and consumption practices and can influence market forces that could lead to embracing alternatives (Mark 2021).

Response option 12: *Develop and strengthen freshwater aggregate governance systems*

Governance systems related to freshwater aggregates are often lacking, are poorly developed (Gallagher and Peduzzi 2019; Mark 2021), or are inadequately enforced (Koehnken et al. 2020). This makes it difficult, if not impossible, to develop and implement effective policy or to have relevant monitoring, enforcement, and compliance. Transboundary governance is a further challenge. Legislative instruments developed at the national level are often inadequately implemented due to a lack of resources at the local level. More effort should also be focussed at the regional level. This will require capacity building (Cuthill and Fien 2005) in the form of providing local governments training on aggregate resource governance, which considers long-term supply and impacts that extend beyond the mining site to the wider environment and these human communities that depend on these freshwater systems. A solid framework for monitoring and reporting river aggregate stocks (suspended sediment load, bedload and erosion) along with extraction volumes is essential. An accurate account of the aggregate budget is fundamental to the sustainable governance of resources (Goichot et al. 2022). Providing mechanisms for miners (including those that engage in more artisanal extraction) and the mining industry to be actively involved in the development of policies and practices will be important to ensure that diverse voices are considered and could increase compliance (Franks 2019). Governance systems are also important for assisting miners with alternative livelihood opportunities to ensure just transitions in instances where freshwater aggregate extraction is reduced or halted. Where good governance exists, it becomes possible to fully integrate policy and legal framework in strategic ways that support responsible sourcing mechanisms (UNEP 2022; see below) and address what have long been largely unregulated supply chains (Da and Le Billon 2022).

Case study: Strengthening aggregate governance systems in the Yangtze River basin, China

In recent years, the negative impacts of overexploitation of sand on freshwater biodiversity in the Yangtze River basin (Chen et al. 2017) have attracted increased attention of the Chinese government at both the central and local levels. In response, there has been an improved aggregate governance system in China that strictly limits the number of sand mining permits, strengthen the overall management of aggregates by governments instead of leasing to private companies as was common in the past, increases the fines on illegal sand mining, identifies sand mining locations and volume limits by considering natural hydrological and sediment conditions in rivers and lakes to meet ecological requirements, and promotes alternatives such as aggregates from land and recyclable sources (Chen 2019).

Case study: Novel approaches to management of river aggregate extraction in California, USA

The Mad River drains 1290 km^2 in the Coast Ranges of northern California, USA, debouching into the Pacific Ocean north of Eureka. It provides habitat for various Pacific salmonids. The river has been an important source of construction aggregate for the regional economy, but overexploitation led to severe channel incision and ecological impacts, which led to environmental disputes. To resolve these disputes, an innovative programme was established to manage aggregate resources in the river. Sand and gravel mining in the Mad River is now managed by the County of Humboldt Extraction Review Team (CHERT), a team of five experts who review changes in bed elevation documented in annual cross section surveys to assess the volume of fresh deposition after each winter wet season, along with data from field reviews at each site, aerial photos, biological surveys, and hydrologic data (Klein et al. 2019). Based on these data, the CHERT team makes specific recommendations on extraction proposals submitted by extractors. These recommendations, along with comments from other regulatory agencies, are used by the County to issue permits for mining specific volumes at specific sites. In wet years with abundant sediment transport, large volumes can be extracted, while in drought years without high flows and "recruitment" of fresh gravel, no extraction may be permitted. The primary federal (national-level) instruments regulating sand and gravel mining in Humboldt County are the US Army Corps of Engineers 2015 Letter of Permission, whose requirements are based in large measure on a Biological Opinion issued by the US National Marine Fisheries Service, whose aim is to preserve runs of native anadromous salmon in the river (Klein et al. 2019). The CHERT process is notable in that it began 30 years ago, in 1992, and it has proved effective since, providing a credible source of scientific oversight and stabilizing river bed levels.

Response option 13: *Implement a holistic Environmental Impact Assessment process*

Individual sites or projects involving aggregate extraction should undertake an Environmental Impact Assessment (EIA) in relation to impacts at a basin scale prior to any mining activities, whereby environmental risks are identified and

Environ. Rev. **32:** 414–437 (2024) | dx.doi.org/10.1139/er-2022-0118

assessed early in the planning or decision-making process. Potential impacts detected by EIAs ideally would include those beyond the boundaries of the extraction sites, such as downstream erosion or groundwater pollution, and indirect impacts including traffic disturbance or alteration to habitat distributions. Unfortunately, a general lack of good quality EIAs and follow-up monitoring has led to broad-scale and indiscriminate aggregate mining, resulting in substantial harm to the environment and ecosystem services, particularly in low-income countries (Peduzzi 2014; Torres et al. 2022). Broadly, holistic EIAs (that include bio-physical and socio–cultural–economic components; Riha et al. 1996) go hand-in-hand with response option 16 (mapping, monitoring, and reporting) and taken together, these efforts further our understanding of aggregate exploitation, ultimately aiming to mitigate or minimize associated impacts (UNEP 2022). For example, an EIA conducted in Southwestern India determined that sand exploitation derived from both streams and floodplains resulted in environmental impacts including habitat degradation, pollution (from oil and gas pollution from vehicles), sedimentation, land stability issues, as well as adverse social impacts (Sreebha and Padmalal 2011). In addition to environmental measurements (i.e., physical, chemical, and biological), the inclusion of traditional and local knowledge would result in more holistic EIAs that would benefit resource use management (UNEP 2022). Increased capacity and efforts to ensure the adequate implementation of EIAs is crucial to increase the effectiveness of the environmental assessment process. Moreover, the use of the most up-to-date knowledge/information, the public reporting of assessment and monitoring outcomes, and the empowerment of local stakeholders or rights holders to apply the EIAs in decision-making would result into more effective assessments.

Response option 14: *Mainstream the mitigation hierarchy for freshwater aggregate extraction projects*

The framework of the mitigation hierarchy for evaluating biodiversity losses and delivering net gains is increasingly used by the mining sector (Arlidge et al. 2018). This framework can guide aggregate extractive activities to limit risks on biodiversity and ecosystem services through four mitigation categories to be implemented sequentially: avoidance, minimisation, restoration, and offsetting (UNEP 2022). An end-goal of no net loss or positive net gain of biodiversity is typically established, relative to a predetermined baseline (Maron et al. 2018). The mitigation hierarchy is implemented through coordination and negotiation across stakeholders, such as government agencies, conservation actors, industries, and developers, with elements of the process often formalized within Environmental and Social Impact Assessments (Arlidge et al. 2018; see the Response option 13 section). Early avoidance mitigation approaches prevent impacts in the planning and design phase of the project, and include, for example, maintaining intact river routes, avoiding protected areas, and identifying alternative mining locations. This requires the identification of un-fragmented migration routes and other sensitive locations, as well as examining the mitigation potential of expected impact, so that impacts that cannot be offset or mitigated, or will deplete irreplaceable critical environmental and biodiversity capital assets (e.g., threatened or poorly known ecosystems and species), together with unacceptable social impacts, are avoided. At the minimisation phase, measures are taken to reduce the duration, intensity and/or the extent of impacts that cannot be avoided, for example, modifying the timing of activities (e.g., seasons and working hours), minimizing lighting and noise or through operational controls. Where possible, thresholds of extraction based on sediment replenishment rates should be formulated. Restoration involves implementing measures to restore ecosystem functionality and complexity following exposure to impacts, using active or passive physical habitat restoration approaches, and any significant residual impacts that may remain are off-set (see the Response option 18 section in the post-extraction phase) by protecting or enhancing freshwater habitats on or away from the project site.

Extraction

Response option 15: *Implement mapping, monitoring, and reporting systems for aggregate resources*

Currently, the extent of overexploitation of aggregates remains unknown due to a lack of mapping, monitoring, and reporting of geological deposits and extractive activities. Without this crucial information, science-based management and strategic planning is next to impossible as the available quantity and quality of aggregates is not known. We acknowledge that some of these activities should occur prior to extraction while other aspects are specific to the extraction phase. While there are more stringent regulations in North America and Europe, in low-income countries that are experiencing rapid development, aggregate extraction often occurs on an informal or illegal basis, therefore circumventing any regulatory or monitoring processes altogether (Koehken et al. 2020). Even in countries with regulations, more extensive monitoring and reporting would permit an examination of spatial and temporal trends of distribution, composition, and dynamics of extraction (UNEP 2022). Globally, most aggregate resources are not yet mapped; therefore, it will be imperative to invest and expand the capacity to do so, and these actions could be undertaken by calling upon Geological Surveys. This mapping should also be converted into versatile databases, permitting actor-specific resource evaluations with links between consumers, traders, and production facilities (Torres et al. 2021). Remote sensing technologies could be used in addition to on-site geological approaches to support the mapping (Hackney et al. 2021; Rentier and Cammeraat 2022). Monitoring in combination with in-depth interdisciplinary research would contribute to a more thorough understanding of the environmental impacts associated with aggregate extraction. To produce more accurate assessments of environmental, economic, and social implications, multi-criteria resource evaluation tools and classification schemes of aggregate resources should be developed (van den Brink et al. 2019). The development and implementation of monitoring, reporting and mapping of aggregate resources would ultimately optimize resource use and minimize overexploitation.

Response option 16: *Develop, test, and adopt best practices for aggregate resource extraction from freshwater systems*

Extraction of aggregate resources will presumably continue at some level in many freshwater systems worldwide for the foreseeable future. As such, it is essential that efforts are devoted to developing, testing, and adopting best practices (Bendixen et al. 2021; UNEP 2022). The first step with developing best practices is to identify sites for extraction that are minimally harmful (Koehnken et al. 2020). This requires a detailed understanding of sediment dynamics throughout the contributing landscape, specifically natural sediment delivery, storage and transport beyond the site, and how reductions in aggregates extracted will alter throughput. In addition, the temporal aspect to this is important, in that what may be a site with minimal biological impacts in one season could be highly damaging in another, given seasonal variability in river processes and the habitat use and environmental requirements of different biota. Another key aspect of developing best practices is to identify extraction practices that are least harmful (Koehnken et al. 2020). Efforts to mitigate impacts during extraction could be fruitful but there are few such options that have been identified. The final step is to identify sustainable mining targets (e.g., volumes) that are relevant to each river, such that they can be broadly applied based on river-specific characteristics. Different river types and sizes have natural variability in sediment load, such that extraction volume limits need to be considered within the range of natural variability (Rempel and Church 2009) to avoid extraction outpacing natural supply with dire consequences (Hackney et al. 2021). The evidence base is currently weak and disparate making it difficult to generate broadly applicable, science-based guidance. Most of the present knowledge on aggregate extraction in rivers focuses on problem identification rather than development of solutions. Clearly, geomorphological principles need to be used to identify sustainable extraction methods. Much of what has been learned is site-specific, focusing on small scales and it is unclear if these methods would scale appropriately to large commercial extraction operations. The few guidance documents that exist tend to be regional (e.g., Department Irrigation and Drainage, Malaysia, 2009).

Case study: Conducting "aggregate audits" to monitor aggregate extraction activities across rivers in India

With an annual requirement of 700 million tonnes (and a 7% increase every year), India is one of the global hotspots of aggregate extraction (in particular, sand mining). While the Central Ministry of Environment, Forest and Climate Change has developed guidelines for the management, monitoring, and enforcement of sand mining, and the various State Governments (e.g., Kerala, Karnataka, and Maharashtra) have their own Acts and Policies, these are often poorly implemented and enforced. In the southern state of Kerala, where intensive mining and extraction have led to the lowering of riverbeds by an average of 7–15 cm/year (19 cm/year in some rivers) since 1980s (Padmalal et al. 2008), an innovative mechanism of assessment and monitoring of sand mining, is now in place. "Aggregate audits" (i.e., assessing aggregate extraction activities in a river/part of a river after a specific period of mining to inform policies and actions) have been undertaken for 21 rivers of the region (Shaji 2021), leading to a total ban on aggregate extraction from six rivers, and restricted extraction approved from five rivers. Similarly, the penalty for illegal mining has been increased 25 times, from US$300 to US$6,000, and imprisonment up to 5 years. A three-tier monitoring system, encompassing a state-level committee for decision-making, a district-level expert committee, and a local self-government (Panchayat) level committee for supervision is also helping ensure sustainability in sand mining activities in the region (Shaji 2021).

Post-extraction

Response option 17: *Promote restoration of degraded ecosystems and compensate for remaining losses*

Human development will sometimes cause unavoidable, however, in these situations provisions for restoration or some form of compensation (off-setting) should be made. Specific to freshwater aggregate extraction, there are opportunities to include such provisions in licensing schemes where there is a policy and legal framework that would enable such measures to be applied. We are now at the beginning of the UN Decade for Ecosystem Restoration 2021–2030 and the interest on river restoration projects is growing (Cooke et al. 2022). It is important to recognize that restoration after intense mining activities is lengthy and rarely leads to complete recovery of pre-disturbance conditions (Kondolf et al. 2007), and that is why phasing out riverbed sand mining is sometimes encouraged (Kondolf et al. 2022). However, projects designed with long term, river-wide, restoration potential in mind can improve the functioning of degraded freshwater ecosystems and biodiversity, and contribute to the provision of certain ecosystem services such as flooding adaptation (UNEP 2022).

Approaches to restoration of habitats, wildlife populations, and natural processes can be passive (self-recovering) or active (relying of human interventions such as environmental engineering). A first step here is identifying best practices for restoration of freshwater ecosystems degraded by aggregate extraction, depending on the intensity and extent of mining, river dynamics, and socioecological contexts (Cooke et al. 2018), determining where like-for-like approaches make most sense, or identifying where other compensation/off-setting related to freshwater habitats (e.g., habitat accounting and banking; Doka et al. 2022) is more appropriate (this requires knowledge about how much off-setting is needed; Moilanen et al. 2009). Reported restoration initiatives predominantly focus on the restoration of riparian habitats and sand and gravel pits in floodplains, whereas the suite of measures applicable in active river channels is less obvious. Instream mining commonly extracts sand and gravel at rates exceeding the natural supply of sediment from upstream, commonly by an order of magnitude or more. Where instream aggregate extraction is regulated, it is often done on the basis of the "replenishment rate" concept, wherein the annual transport of sand and gravel is estimated or measured, and the annual extraction is limited to this rate (Kondolf 1994). The idea is that sediment removed by mining in a

 Environ. Rev. 32: 414–437 (2024) | dx.doi.org/10.1139/er-2022-0118

reach will presumably be replaced by fresh sediment transported from upstream. However, management must consider that the river still has energy (e.g., sufficient flows) to transport its full load downstream of the mining reach, so extraction would need to be limited to some fraction of the replenishment rate, otherwise the mining reach and downstream reaches would be affected. While the concept of mine "reclamation" has been inappropriately applied to instream sand and gravel mines (Kondolf 1993), projects that actually restore river processes and forms to mined reaches have been rare, but are possible. As mining typically extracts many years' worth of supply annually, there may be no way to reverse this impact without bringing in gravel to replace the coarse sediments lost to mining. In the Sacramento–San Joaquin River System, large restoration projects have been undertaken to isolate or and partially fill disused sand and gravel pits to reduce predation of juvenile salmon by non-native species inhabiting the pits (Kondolf et al. 2008). What is also needed are assurances that extraction would not occur without restoration and compensation plans in place (which could be in the form of levies, royalties, or other legal assurances) including financing to cover the costs. For example, in Makueny county in Kenya, 50% of the revenues from authorized sand mining operations are used to support restoration and conservation activities, such as building sand dams (UNEP 2022). Licensing conditioned upon mitigation measures is common with hydropower developments (Opperman et al. 2011; Schramm et al. 2016) and is situated within a changing landscape where compensation/off-setting are baked into policy (e.g., Villarroya et al. 2014). It is crucial to implement mechanisms to ensure that the funds obtained for compensation are directed towards local environmental and social improvements. Given the importance of monitoring in restoration (Lindenmayer 2020), funds for monitoring restoration outcomes should be included to ensure they achieve the proposed targets and to provide opportunities for learning to inform future restoration and compensation. Involving stakeholders and rights holders in setting and prioritizing restoration goals will help to ensure that efforts achieve societal and environmental benefit.

Case study: Post-extraction restoration of the upper Drac River, Southeastern France

The Drac River drains 3300 km^2 in the French Alps, joining the Isere in Grenoble. Aggregate mining in the upper reaches of the Drac (above Saint-Bonnet-en-Champseur) in the late 19th Century resulted in bed incision 2–4 m downward through a surficial layer of gravel into underlying glacial clay. By about 2010, the channel had reached the clay, through which it rapidly incised downward, converting what had been a broad, gravel bed with shallow water table and a thriving riparian woodland into a narrow ditch cut into clay. This dried out the gravels and the riparian forest, leading to invasion of scrubby upland trees adapted to xeric conditions. To restore the form and function of the river's bottomland, an ambitious restoration project was undertaken in 2014 (Vento et al. 2016): the incised river channel over 3.5 km was filled with gravel, and weirs were installed above and below the restored reach to prevent regressive erosion up into the restored reach. About 355 000 m^3 of gravel was used to fill the channel, which was obtained from the gravel composing the formerly wide channel abandoned by the incision, and 67 000 m^3 brought in from external sources. The project increased the average active channel width from 38 m (post-incision and pre-restoration) to 110 m, and increased the elevation of the water table by 3 m on average (Laval et al. 2022). Since completion of the project, the reach has generally aggraded on the order of 15 000 m^3 (an average aggradation of about 2.5 cm) during floods with return periods of a 2–3 years, while a 10 year flood in 2021 produced incision of about 5 cm ("de-stocking" of around 30 000 m^3). Thus, the situation appears sustainable so far (F. Laval, personal communication).

Response option 18: *Develop mechanisms that enable responsible sourcing of aggregates*

Across the spectrum of aggregate extraction organizations and operations, there is a wide range of mitigation strategies during extraction to minimize environmental impacts. As such, there are opportunities for those engaging in infrastructure projects to also engage in responsible sourcing (admittedly this transcends pre- and post-extraction), thus creating market forces that can encourage other extractors to adopt sustainable behaviours. Fundamental to such efforts is the need to identify which practices are more environmentally and socially sound, and ensure that these practices can be linked to a given batch of aggregates. Key questions include: what is the geographic location of aggregate extraction; what was the source of extraction; was an EIA conducted and approved; what type of mitigation is/was planned/used; is there a monitoring system in place; and what mechanisms are in place to finance restoration or compensation efforts? Funders of large infrastructure projects that often include public funds have a critical role to play in responsible sourcing and accountability of supply-chain impacts (UNEP 2022). Responsible sourcing strategies should also contribute to increase the traceability of aggregates, help to address corruption and criminal activity, and overall promote the transparency of sand supply networks. The specifics of responsible sourcing and supply chain management is complex and beyond what can be fully explored here so we direct readers to further discussion in the UNEP report on sustainable sand mining (UNEP 2022).

Next steps for overcoming implementation challenges

Overexploitation of biological and aggregate resources has occurred for decades, if not centuries, and continues and is increasing to this day. The reasons are varied. The lack of scientific knowledge about the consequences of these activities and interventions for mitigating impacts have constrained progress to some extent (Harper et al. 2021). It is now clear that overharvest of resources is problematic, but we have a growing toolbox of response options and lack of knowledge can no longer be considered justification for inaction (Tickner et al. 2020). As such, it is apparent that the biggest issues related to implementation are centred around people, institutions, and governance as outlined below.

Increase public awareness

From bleaching of coral reefs to bycatch of dolphins in coastal waters, the general public is well aware of the threats facing marine ecosystems and biodiversity. Yet, when it comes to freshwater systems, threats tend to be poorly recognised and forgotten (Cooke et al. 2013). Part of it is because in many waters, freshwater life is invisible (Kochalski et al. 2019). The value of freshwater fishes as an essential source of food is generally poorly appreciated compared with marine fish, despite the their importance in many low-income countries of the world. Moreover, freshwater life is often thought of as being somewhat boring—fish that are not very colourful or lack of megafauna. Yet, that is incorrect. The real failure has been in making freshwater life more visible (Monroe et al. 2009). Such barriers can be addressed through storytelling, celebrating freshwater life (e.g., at aquaria or botanical gardens or festivals), and incorporating freshwater biodiversity into elementary and secondary school curriculum. Such efforts need to be regionally targeted to ensure they reflect local cultures, values, norms, and beliefs (Riepe et al. 2021). Given the dire state of freshwater biodiversity, there is need to learn from what is known across regions to help generate fit-for-purpose best practices that apply to diverse scenarios (Cooke and Birnie-Gauvin 2022).

Cultivate political will to enact appropriate protections

To date, there has been little effort by politicians and governments in most regions to enact regulations that adequately address overexploitation of biological and aggregate resources. The lack of political will is presumably connected to lack of awareness of the plight of fresh waters by members of the public and beliefs that aggregates are renewable, infinite resources, such that there is no "pressure" to enact change (Cooke et al. 2013), or supply chains and business as to the risk unhealthy freshwater ecosystems place upon their operations. Similarly, politicians are unaware of the value provided by sustainable extraction and the connection between intact freshwater ecosystems and human well-being, nutritional security and livelihoods. To achieve the political will needed to better manage freshwater resources will require pressure from diverse publics and sectors (i.e., voters—acknowledging that in remote and/or impoverished regions voting is uncommon); diverse water users within a basin; the whole value chain connected with a basin) as well as efforts to characterize the value of these resources so that there is a strong value proposition for sustainable management (Beard et al. 2011); and making difficult decisions that may favour long term benefit over short term gain.

Create mechanisms to share successes and failures

Learning by doing is a common strategy when it comes to environmental interventions but if that learning is not shared, the benefits may only accumulate on a local basis. Given the dire state of freshwater biodiversity, there is need to share what works (and what doesn't) across regions to help generate best practices (Cooke and Birnie-Gauvin 2022). Networks of freshwater practitioners that enable knowledge exchange are needed to provide avenues for sharing. This is not to say that what works in one context will always work in another but given the challenges we faced in identifying case studies that represented success stories for given measures is illustrative of the fact that the peer reviewed literature is not always a repository for on-the-ground actions especially when actions are ineffective. Scientists working together with practitioners is another mechanism where efforts can be studied, documented, and shared through peer reviewed literature to codify knowledge and build the formal evidence base. Given that freshwater conservation literature is underrepresented in the literature (He et al. 2021), such efforts are sorely needed.

Put the spotlight on a hidden crisis

Even in well-managed fisheries, collapse can occur from overharvest. Post et al. (2002) detailed a number of reasons why collapses of freshwater fish populations attributed to overharvest were not noticed. Most notably was the lack of ongoing monitoring (Post et al. 2002). Moreover, human behaviour is complex, such that when harvest in one area or for one species declines, then effort shifts to a different location or species (Fulton et al. 2011). Of course, that assumes that there are alternatives. Another assumption is that because most harvesting in fresh waters does not use the same equipment that is used in industrial commercial fishing in the high seas overfishing is simply not possible. However, diffuse effort from small-scale fishers or even recreational fishers can lead to overexploitation (Post et al. 2002). Better monitoring programs that are interfaced with management systems (as part of the assessment–monitoring cycle) and paying close attention to the behaviour of harvesters could help to reduce overexploitation.

Prioritize respectful engagement with resource users

Engagement with resources users (including rightsholders, e.g., Indigenous Peoples) is well known as being foundational to effective environmental management (Reed 2008). Yet, there are many instances where this does not occur. Given that the behaviour of individual fishers and aggregate miners has the potential to determine the extent to which activities are sustainable, it makes sense to formally include them in planning and management. When resource users are involved in management they take ownership of the resource and tend to have high levels of compliance (Ali and Abdullah 2010), which encourages social learning and leads to reflections on their individual roles in the resource (Turner et al. 2020). In the case of rightsholders (the UN Declaration for the Rights of Indigenous Peoples requires their involvement in the management of resources (such as freshwater fisheries and other organisms) as they exercise their sovereign rights. Co-management of freshwater fisheries resources is becoming more common (Song et al. 2020) and has much potential for addressing the freshwater biodiversity crisis, if undertaken with the full involvement in the planning and implementation phases.

 Environ. Rev. 32: 414–437 (2024) | dx.doi.org/10.1139/er-2022-0118

Recognize the complex intersection between exploitation of biological and aggregate resources

There are remarkable similarities between fisheries exploitation and aggregate extractions, and at times they intersect in complex ways. In Indonesia, fishers that target both inland and marine fisheries using small-scale gears have observed declines in harvest requiring them to supplement their livelihoods with alternative activities, including sand dredging (Untari et al. 2022). Sand dredging is spreading into many fishing communities in parts of Sub-Saharan Africa (Jonah and Adu-Boahen 2016; Sowunmi et al. 2016; Vieira and Rocha 2021) and Southeast Asia (Lamb et al. 2019), adding additional stressors on the health of the fishery. By monitoring harvest of biological and aggregate resources it ensures that licences for dredging can be given in non-fishing areas and vice versa. This has the potential to reduce not only the environmental degradation from the activities and potential conflict between resources users, but also help sustain freshwater habitats.

Build effective policy instruments to sustainably manage freshwater biological and aggregate resources

Whether globally, nationally, or regionally, there is generally a lack of leadership or policy when it comes to freshwater biological and aggregate resource extraction and sustainable management. These issues have been discussed above but are worth re-stating here. In terms of biological resources, the UN FAO "Ten Steps to Sustainable Inland Fisheries" (see Taylor and Bartley 2016) represents an important first step, yet additional effort is needed to downscale such guidance and develop action plans (Cooke et al. 2021). With respect to aggregate resources, the UNEP has developed "Ten Strategic Recommendations to Avert a Crisis" (https://www.unep.org/resources/report/sand-and-sustainability-10-strategic-recommendations-avert-crisis). These show much promise but are also new so there has been little time for implementation. Both of these developments suggest that exploitation of biological and aggregate resources is finally being recognized on the global policy stage and require immediate and affirmative action. However, implementation will require multi-scalar governance and engagement of practitioners, resource users, rights holders, and diverse publics.

Conclusion

Tickner et al. (2020) provided the foundational elements of an emergency recovery plan for freshwater biodiversity. Here we have provided a comprehensive and nuanced assessment of the suite of response options (Table 1) that are available to help prevent, minimise or mitigate over (or unsustainable) exploitation and ensure sustainable management of biological and aggregate resources in freshwater ecosystems. The response options are supported by a series of case studies that are intended to provide diverse examples of where they have been applied with some success. There are certainly more examples than we could provide here and some of the examples used are still in progress and have yet to achieve all of their desired objectives. Not all case studies will be directly transferrable given local contexts. Indeed, even the response options need to be considered in terms of local context and in some cases the generalizations made here could be counter productive. To that end, we want to emphasize that the guidance provided here is not intended to be prescriptive but is intended to empower relevant actors and institutions to consider response options and tailor them to their given context. It may not be intuitive why we have combined biological and aggregate resources in a single treatment given that the evidence bases are rather discrete. Yet, they have similarities in terms of the phases involved (i.e., pre-extraction, extraction, and post-extraction; see Fig. 3) and fundamentally are about ensuring that materials are harvested in ways that are sustainable. It is also worth emphasizing that these issues should be addressed simultaneously or else efforts at solving just one or the other will be futile. Neither biological nor aggregate resources in freshwater ecosystems are unlimited, so there is an urgent need to manage exploitation as part of broader initiatives needed to protect and restore freshwater biodiversity around the globe.

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