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Instream sediment mining in Chilean rivers: review and management proposal

Extracciones de sedimento en ríos chilenos: revisión y propuesta de gestión

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Abstract

The effects of instream sediment mining have been widely described in the literature. Although this activity has been strictly regulated in some countries, other countries still register an increasing number of sediment mining extractions, as is the case of Chile. The goal of this work is to study the current state of instream gravel mining in Chile, describing the current legislation in the country. The results showed an increasing trend in the number of approved projects, and although present in the whole country, a large proportion were located in the central and southern regions, led by Ñuble Region. The regulation of mining activities in the country is currently managed and evaluated by the municipal government where the extraction is located, after an evaluation from the Department of River Works, which has led to an over-extraction situation in some rivers. Within this context, there has been a raise in the Chilean society awareness regarding environmental issues, accompanied by the identification of the main negative impacts of sediment mining from fluvial systems. Recently, the Chilean government has been discussing a new instream sediment mining law, with the aim to standarise the regulations and incorporating a socio-environmental vision in the evaluation of these projects.

Keywords: sand mining, gravel mining, legislation, Chile.

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Resumen

Los efectos de las extracciones de áridos en ríos han sido ampliamente estudiados en la literatura. Aunque esta actividad ha sido estrictamente regulada en algunos países, en otros todavía incrementa el número de extracciones, como es el caso de Chile. El objetivo de este trabajo es estudiar el estado actual de las extracciones de áridos en ríos chilenos, describiendo también la legislación actual del país. Los resultados mostraron una tendencia creciente en el número de proyectos aprobados y, aunque están presentes en todo el país, una gran parte de ellos se ubican en la región centro-sur, siendo Ñuble la región con un mayor número de extracciones. La regulación de las actividades de extracción de áridos en Chile se gestiona y evalúa por parte de los gobiernos municipales, después de una evaluación por parte del Departamento de Obras Fluviales, lo que ha conllevado una sobre-extracción de sedimento en algunos ríos. En este contexto, la sociedad chilena ha experimentado un incremento en la conscienciación ambiental, acompañada de la identificación de los principales efectos de las extracciones de áridos en ríos. Recientemente, el gobierno chileno ha discutido una modificación de la ley de extracciones de áridos, con el objetivo de estandarizar la regulación de esta actividad e incorporar una visión socio-ambiental en la evaluación de estos proyectos.

Palabras clave: extracciones de arenas, extracciones de gravas, legislación, Chile.

1. Introduction

Over the past decades, natural resources have been exploited on such a large and widespread scale that derived in long-lasting consequences. The pervasive action of humans can be systematically recognised on sedimentary records (Owens, 2020), and the increasing dominance of human activities on sedimentary Earth system processes changed so much that they no longer resemble those of the Holocene (Cendrero *et al*., 2022). For example, Syvitski *et al*. (2022) recently reported that human activities have increased fluvial sediment delivery by 215%, while simultaneously decreasing the amount of fluvial sediment that reaches the ocean by 49% due to river damming, and societal consumption of sediment, mainly sediment mining, over the same period has increased by more than 2,500%.

Sediments are used in a range of human activities and domestic and industry production processes, and with population growth, which is expected to reach about 9.7 billion inhabitants in 2050 (Simanjuntak *et al*., 2023), the demand of these resources is likely to increase, reaching a point at which it will exceed the rate of natural renewal (Bendixen *et al.,* 2021). Along with other resources, sand and gravels have an important role in construction, which lead to large extractions of sedimentary material from mining areas, especially in fast developing countries. According to the UNEP (2014), sand and gravel mining represent the highest volume of raw material used on Earth after water, and that may continue growing as it is a global phenomenon, especially intense in countries registering a rapid urban growth (Sear and Archer, 1998; Bendixen *et al*., 2021).

Although the origin of aggregates may vary depending on the geographic context, in many cases they are obtained directly from alluvial deposits since it has some advantages with respect to other mining sites (Kondolf, 1994a; Sear and Archer, 1998). As stated by Kondolf (1994b), the main advantages are: (i) the material is durable, rounded, well-sorted, and relatively free of interstitial fine sediment; (ii) the source of material is generally located near the markets for the product, what reduces transportation costs; and (iii) the extraction and processing of material in instream mining has a relatively low cost and the sediments are expected to be periodically replaced from upstream during high flow events. Although sediments can be extracted from moraines, terraces and abandoned alluvial fans, in most cases they are extracted from riverine areas (i.e., floodplains, bars, and active channels). River mining activities usually result in significant consequences along the river that may last from decades to hundreds of years (Hayer and Irwin, 2008; Arróspide *et al*., 2018). Sand and gravels from rivers are usually extracted with heavy equipment either from pits in floodplains and terraces, or directly from the riverbed (i.e., instream mining; Kondolf *et al*., 2001). Although floodplain mining may have important effects on the fluvial ecosystem (Kondolf, 1994a), the effects of instream gravel mining are detrimental for rivers due to the consequent physical, chemical, and biological changes in the stream ecosystem. Instream gravel mining usually causes upstream and downstream channel incision (Wyżga, 2001; Batalla, 2003; Brestolani *et al*., 2014; Kiss *et al*., 2017), lateral channel instability (Roberge, 2002), alteration of substrate composition and stability (Hajdukiewicz and Wyżga, 2018), water table lowering (Rinaldi *et al*., 2005), punctual increase in sediment load and turbidity (Hayer and Irwin, 2008; Béjar *et al*., 2017), alteration of physical and chemical water characteristics (Hayer and Irwin, 2008), loss of riparian and aquatic habitats (Asabonga *et al*., 2017), and changes in stream structure and function (Carling, 1984; Brown *et al*., 1998; Rempel and Church, 2009; Mori and Brancelj, 2011; Mori *et al*., 2011; Booth *et al*., 2020). Some of these impacts, in particular river incision, can result in damage to bridges and other infrastructure due to a reduction in load-bearing capacity, eventually leading to their collapse (Kondolf, 1997; Rinaldi *et al*., 2005; Chen *et al*., 2018). In addition to environmental and ecological problems, river mining thus contributes to the increasing vulnerability of critical infrastructure (Kondolf, 1997).

Given the increasing body of evidence demonstrating the negative long-term consequences on riverine ecosystems, instream sand and gravel mining is strongly regulated in countries such as Portugal, Italy, Spain, New Zealand, USA, and Canada, and is mostly banned in countries such as France, Holland, UK, Germany, and Switzerland (Kondolf, 1997; Gavriletea, 2017). However, the number and size of instream gravel mining sites have progressively increased in the last years in fast developing regions (e.g., Latin America), mainly because of the urban expansion and land use changes. Instream sand and gravel mining in Chile is still permitted, due to the need for building material and, therefore, Chilean rivers are becoming increasingly affected by this activity (Fig. 1). Despite the wide and intense presence of river mining sites in the country, very few studies analysed the current state of this activity. Many recent studies reported on the characterization of the hydro-morphological patterns of Chilean rivers (Bañales-Seguel *et al*., 2020; Ulloa *et al*., 2020; Habit *et al*., 2022) and human impacts due to dam closure (Alcayaga *et al*., 2019, Villablanca *et al*., 2023) and flow regulation (e.g., Pacheco *et al*., 2022), but only Arróspide *et al*. (2018) evaluated the effects of instream gravel mining in a 22 km-long reach in a Chilean river. Specifically, these authors assessed gravel extractions on the morphological characteristics (e.g., active channel width, variation in thalweg elevation, connectivity) in the Maipo river, reporting striking evidence such as recent narrowing in the range of 15 m per year and incisions as high as 35 cm per year. They also reported that gravel mining area increased by 325% from 1998 to 2018.

The goal of the present work is to study the state of instream gravel mining in Chile. Due to the lack of published data, there are no works assessing the potential effects of instream sediment mining in Chile. Hence, this work is the first attempt of establishing the conceptual frame and the state of the art of this activity in the country. The specific objectives of the study are: (i) to describe the distribution and evolution of instream sediment mining in Chile according to official data, and (ii) to analyse the current regulations and rules related to the sand and gravel mining industry in Chilean rivers. For the specific objective (ii), a review of the instream aggregate mining legislation was included for contextualisation. In addition

Figure 1. Gravel mining sites in Chilean rivers that reflect the simplified morphology and the lack of sediment in these river reaches. a) Aconcagua river (Región de Valparaíso); b) Aconcagua River (Región de Valparaíso); c) Maipo River (Región Metropolitana); and d) Peuco River (Región del Libertador Bernardo O'Higgins).

Figura 1. Extracciones de áridos en ríos chilenos que reflejan la morfologia simplificada y la falta de sedimento en los tramos de río. a) Río Aconcagua (Región de Valparaíso); b) Río Aconcagua (Región de Valparaíso); c) Río Maipo (Región Metropolitana); and d) Río Peuco (Región del Libertador Bernardo O'Higgins).

to highlight the gaps of current research on river sediment mining in the country, this work is expected to contribute to the informed public discussion on the topic that is going on in the country, and lead to monitoring and research programs to facilitate decision-making and planning of these activities.

2. River sediment mining legislation in Chile

The administrative setting and legislations on water and river management in Chile is rather complex and involves many governmental agencies involved in the system (Valdés-Pineda *et al*., 2014). Moreover, the current legislation on river gravel mining in Chile is abundant but dispersed in different legal and regulatory bodies (Orrego *et al*., 2016), and it lacks a detailed definition of what is to be considered gravel or aggregate (Figueroa, 2000; Bermúdez Soto, 2007), which generates difficulties in terms of interpretation of existing regulations. In fact, under the current legislation, clays, sands and gravels are not considered minerals and are therefore not affected by the Mining Law (*Ley de Minería*) but are subjected to other administrative bodies depending on the property of the land (i.e., private or public). If the land is private, the governing law is the Civil Law (*Código Civil*), and when the land is public, it must be differentiated between national assets for public use and fiscal assets. Rivers are national assets for public use and its administration and management depends on municipal governments (Valdés-Pineda *et al.*, 2014). Instream sediment mining has been regulated by the law about river and stream beds (Law 11.402 (1953) about river and stream beds and banks; Romero *et al*., 2014). This law establishes that although the local government is the responsible for granting the permissions for mining activities, the activities related to instream aggregates extraction require a technical approval from the Hydraulic Works Authority (*Dirección de Obras Hidráulicas, Ministerio de Obras Públicas*).

Also, due to the potential environmental impact of this activity, the Law 19.300 of 1994 (General Bases for the Environment), in its article 10 - letter *i* - 5.2, established the required approval of the gravel extraction project by the SEIA when sediments are obtained from rivers or other water bodies and the total extracted volume is higher than 20,000 m^3 in the northern regions (from Arica to Coquimbo), or higher than 50,000 m^3 in the southern regions (from Valparaíso to Magallanes). These are considered as 'industrial' extractions. The SEIA (*Sistema de Evaluación de Impacto Ambiental*, which is the Chilean Environmental Impact Assessment System in English) has the function to assess the alterations or impacts that the proposed activities will or may influence the environment and, according to the evaluation, approve or disapprove them. There is no defined procedure in the legislation for obtaining the referred permits, depending on the municipal ordinances (Figueroa, 2000). However, the basis of the procedure tends to be the same in all cases, consisting of three phases: (i) the application, (ii) the report of the Department of River Works (DOF, *Departamento de Obras Fluviales*), and (iii) the constitutive resolution. The application to the pertinent municipality (i) consists on the submission and evaluation of complementary studies on the area of the project: i.e., topography, aerial photography, hydrological analysis, hydraulic study, erosion assessment, and a detailed extraction program. Also, according to Law 19.300, and depending on the potential risks of the activity, an Environmental Impact Statement (EIS) or an Environmental Impact Assessment (EIA) is needed for its approval. The DOF (ii) requires the issuing of a technical report once the respective Municipality confirms that all the requirements of the application have been met. This report is mandatory according to Article 11 of Law 11.402. The constitutive resolution (iii) consists on the Mayor pronouncement with the agreement of the Municipal Council (Figueroa, 2000). The technical requirements depend on the aggregate extraction process, whether industrial or not. For non-industrial exploitation, minimum operating guidelines and conditions are required, and these are based on the characteristics of the river reach to be exploited and on other elements pointed out by the DOF. For industrial extraction, an environmental impact assessment and compliance with current environmental regulations are mandatory. Although the process is well-established, there is the risk of incorrect use of the permits, since some extraction projects can either be fragmented or underestimated the amounts of material planned to extract to avoid the SEIA evaluation.

Since 2022, the Chilean government has been working on a draft for an updated legislation for aggregate mining, with the aim of generating a general policy framework for Chile to ensure an effective and efficient regulation of this activity (proposal of *Ley Áridos*, Boletín 15.096-09 and Boletín 15.676-09), which should be considered in the context of a basin (i.e., included in watershed management plans and land-use planning). The Senate approved the creation of this new general policy framework for the aggregate extraction in the beginning of 2024, and is currently being processed. In this recent law proposal, the definition of aggregates is extended, and specifies that clay, sands, gravels and other aggregate materials directly used in construction would be under the effects of this law. The aim of this law is to standardize the regulation related to aggregate extractions, with control of the origin and tracking of the aggregates. The proposal includes a socio-environmental vision with, for instance, the consideration of environmental studies when evaluating the applications or the obligation to mitigate the effects once the activity is finished. Moreover, the proposal incorporates the regulation of river aggregates, according to the river dynamics and condition.

3. Methods

To assess the distribution of the instream mining sites in Chile, a search of submitted and implemented instream mining projects in the database of the Environmental Evaluation Service (SEA, *Servicio de Evaluación Ambiental*, in Spanish) up to December 2021 was carried out. The SEA is a functionally decentralized public institution with legal personality that is responsible for determining the suitability of an activity according to the Chilean environmental legislation. This institution was created by Law Nr. 20.417, published in the Official Gazette on January 26th 2010, which amended Law Nr. 19.300 on General Bases of the Environment. According to the legislation, the activities with significant environmental impacts require an Environmental Impact Study, while the other activities only require an Environmental Impact Statement, as mentioned above.

The search of the submitted and approved instream mining projects was carried out using the advanced search of the online platform in the SEA webpage (https://seia.sea.gob.cl/busqueda/buscarProyecto.php). The mining projects were selected and, among them, the search was narrowed to mining projects including coal, oil, exploration, mining, processing plants and waste and tailings disposal, and industrial extraction of aggregates, peat or

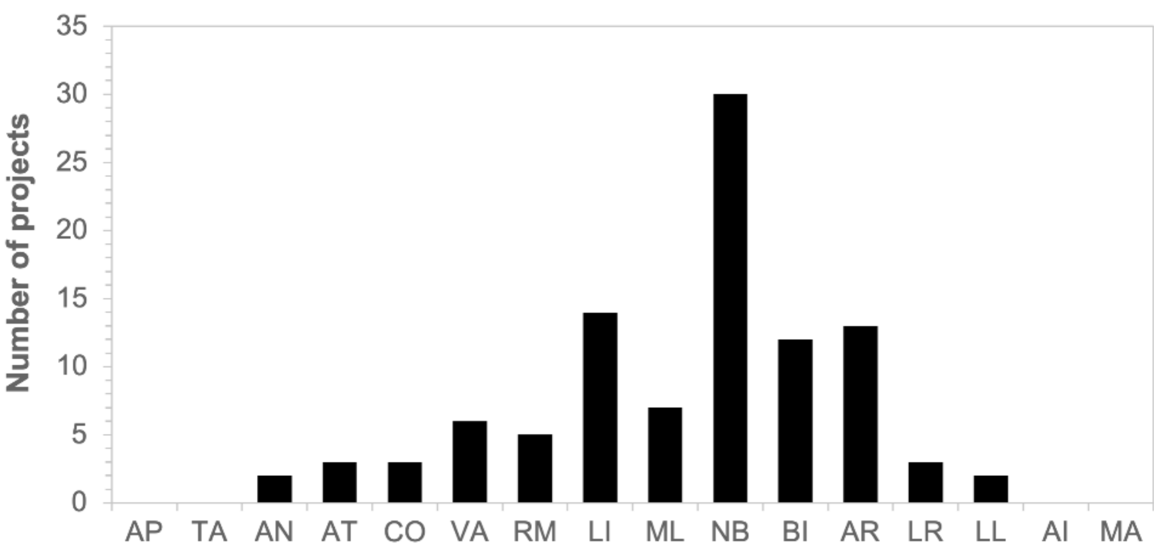

Figure 2. Distribution of approved instream mining projects per region from North to South (1997-2021). AP: Arica y Parinacota; TA: Tarapacá; AN: Antofagasta; AT: Atacama; CO: Coquimbo; VA: Valparaíso; RM: Región Metropolitana; LI: Libertador General Bernardo O'Higgins; ML: Maule; NB: Ñuble; BI: Biobío; AR: Araucanía; LR: Los Ríos, LL: Los Lagos; AI: Aysen; MA: Magallanes.

Figura 2. Distribución de proyectos aprobados de extracción de áridos en ríos por región de Norte a Sur (1997-2021). AP: Arica y Parinacota; TA: Tarapacá; AN: Antofagasta; AT: Atacama; CO: Coquimbo; VA: Valparaíso; RM: Región Metropolitana; LI: Libertador General Bernardo O'Higgins; ML: Maule; NB: Ñuble; BI: Biobío; AR: Araucanía; LR: Los Ríos, LL: Los Lagos; AI: Aysen; MA: Magallanes.

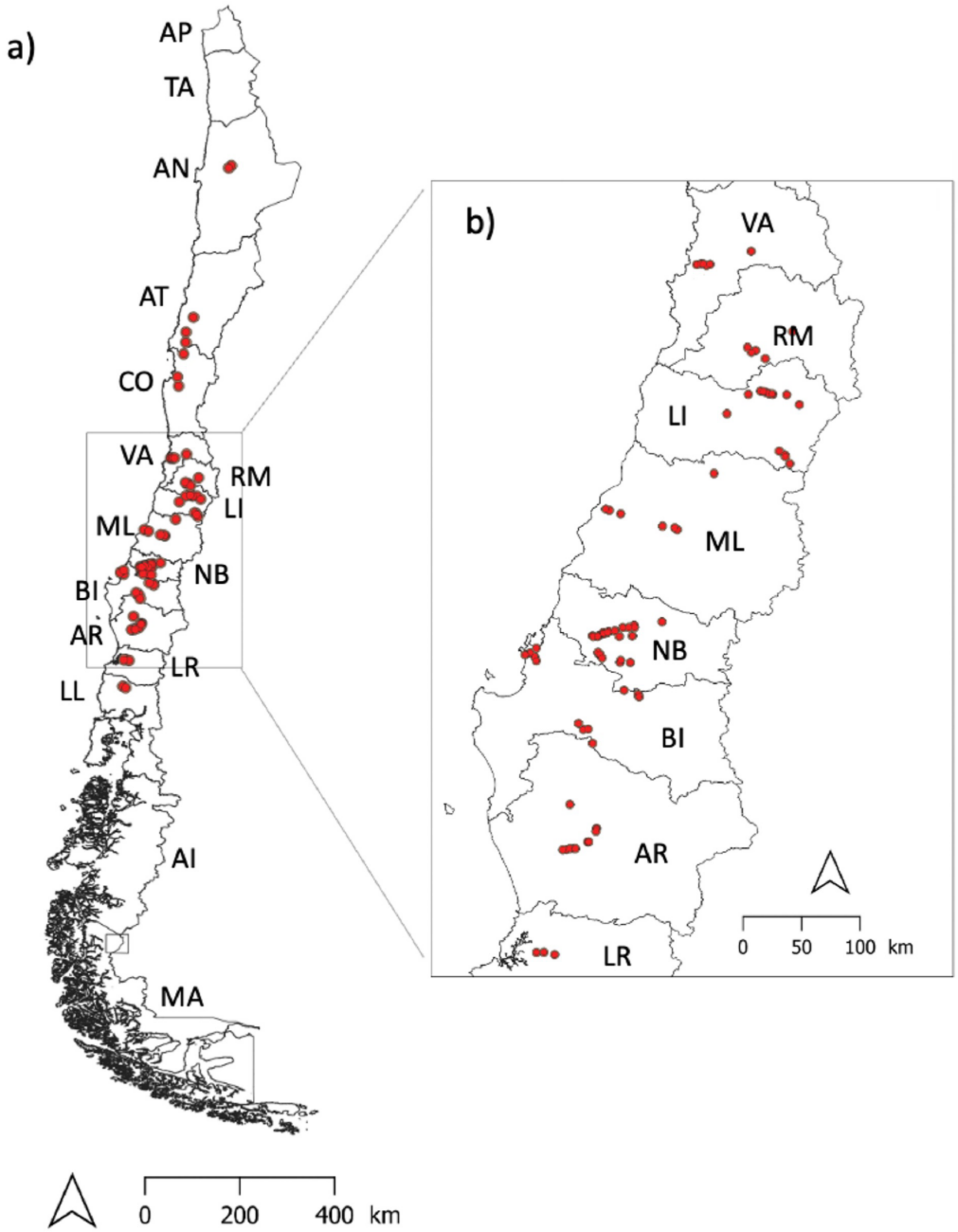

Figure 3. a) Distribution of approved instream mining projects per region (1997-2021); b) Zoom to the regions with higher concentration of mining sites. AP: Arica y Parinacota; TA: Tarapacá; AN: Antofagasta; AT: Atacama; CO: Coquimbo; VA: Valparaíso; RM: Región Metropolitana; LI: Libertador General Bernardo O'Higgins; ML: Maule; NB: Ñuble; BI: Biobío; AR: Araucanía; LR: Los Ríos, LL: Los Lagos; AI: Aysen; MA: Magallanes.

Figura 3. a) Distribución de proyectos aprobados de extracción de áridos en ríos por región (1997-2021); b) Ampliación del mapa de las regiones con mayor densidad de extracciones. *AP: Arica y Parinacota; TA: Tarapacá; AN: Antofagasta; AT: Atacama; CO: Coquimbo; VA: Valparaíso; RM: Región Metropolitana; LI: Libertador General Bernardo O'Higgins; ML: Maule; NB: Ñuble; BI: Biobío; AR: Araucanía; LR: Los Ríos, LL: Los Lagos; AI: Aysen; MA: Magallanes.*

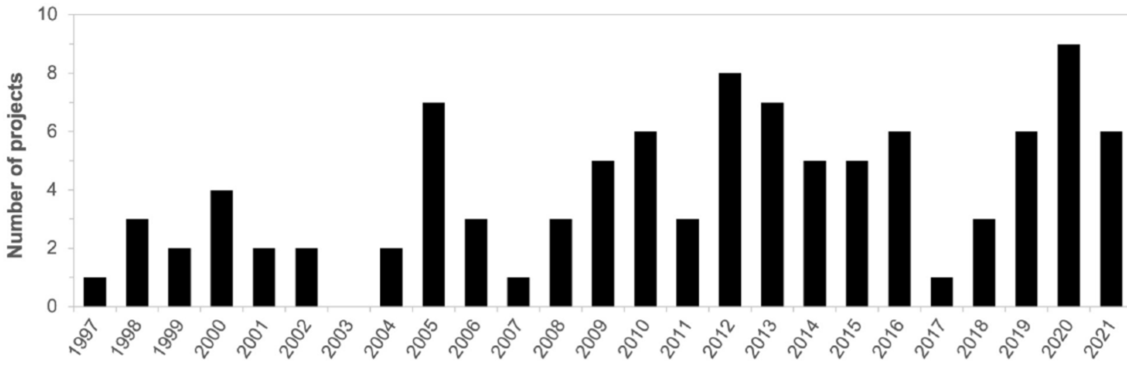

Figure 4. Evolution of approved instream mining projects in Chile (1997-2021).
Figura 4. Evolución de proyectos aprobados de extracción de áridos en ríos en Chile (1997-2021).

chalk. The search was refined to the selection of only those projects related to the extraction of aggregates, resulting in 524 projects. Among them, 224 project were accepted or on qualification at the time of data processing, while the others had been withdrawn, rejected, or not admitted for processing. A one-by-one visual screening using Google Earth Pro[R] was then performed to identify and select only the mining sites located in rivers or next to rivers. This process resulted in a total of 100 approved instream mining sites. All these 100 sites are considered as 'industrial' due to the volume planned to be extracted, which include the extractions of sediment bigger than 20,000 m^3 or 50,000 m^3 depending on the region.

4. Results: the distribution and evolution of instream mining in Chile

According to the projects submitted to the SEIA from 1997 to 2021, the Ñuble region concentrated most of the gravel extraction projects (30 projects), followed by Libertador General Bernardo O'Higgins, Araucanía and Biobío regions (14, 13 and 12 projects, respectively; Fig. 2 and Fig. 3). These four regions are in the central part of the country, together with Maule region that had a lower number of river mining sites.

Although there is a high variability in the number of approved projects per year, an increasing trend can be observed from 1997 to 2010, and a decreasing trend from 2012 to 2021 (Fig. 4). Despite the high number of approved projects, the rate of growth showed some recessive stages from year 2006 to 2008 (Fig. 4), which could be due to transitory and short disturbances from other sources of the economy, as the recession in Chile between 2008 and 2009, generated by the systemic effect of the international financial crisis (Cerda and Vergara, 2008).

5. Discussion

5.1. Instream mining in Chile

Although 100 river aggregate minin sites were identified after the search in the SEIA, according to the Chilean Ministry of the Environment (MMA, 2022), 330 gravel mining projects have been approved between 1997 and 2021, and up to 20% of these projects will run until 2030. However, according to Alvarez Mardones (2019), only 245 legal instream gravel mining exploitation projects began between 1997 to 2019. This fact could be explained because, according to the Law Nr. 19.300, only industrial gravel extractions (i.e., ≥ 20,000 m^3 in the case of regions from Arica y Parinacota to Coquimbo or ≥ 50,000 m^3, from Valparaíso to Magallanes and Antártica Chilena regions, including the Metropolitan Region, during the useful life of the project) must be evaluated by the SEIA.

Most of the population in Chile is concentrated in the central part of the country (i.e. from Región de Valparaíso to Región de la Araucanía inhabits the 79% of the population), but most of the mining sites were located from Región del Libertador Bernardo O'Higgins to Región de la Araucanía. In fact, most of the aggregates obtained are being commercialised in the Metropolitan, Biobío and Valparaíso regions (CChC, 2022), which concentrate the 60% of the population in the country. This distribution of extractions may be due to the high urban population living in the Metropolitan and Biobío regions (INE, 2018) where the demands of raw material are thus higher. Connections between the regions with a higher number of instream mining sites and regions with higher population are easy through the central valley in the country. In fact, most of the mining sites are located in this central valley, where most of the main cities are located, and river reaches there are characterised by low slopes and appropriate sediment grain sizes for construction, in comparison to the river reaches in the confined valleys of the mountain range (higher slopes and larger sediment particles not ready to use in construction). Accessibility is also important, and all those regions are under the influence of the Mediterranean climate and river reaches in the central valley have a hydrological regime characterised by a long period of low discharges in summer, or are located downstream from a reservoir, thus with low flows most of the year. Both of these situations with low water level in the river facilitate the accessibility to river sediments.

Despite that instream mining is widespread in Chile, scientific research about its impacts on the rivers in the country is still rather limited. To the best of our knowledge, only Arróspide *et al*. (2018) assessed the effects of instream mining in the country, focusing on the morphological effects of this activity in the Maipo river (Metropolitan Region, Central Chile). The Maipo river is of high interest in the country since (i) it concentrates the largest amount of instream gravel mining activities in the country (Arróspide *et al*., 2018), (ii) the region concentrates more than the 40% of the national population (INE, 2018), and (iii) economically, it is one of the most important rivers in the country as it provides drinking and irrigation water to both urban and rural areas, generates electricity, and runs along and below critical infrastructure (Cai *et al*., 2006). Consequently, the Maipo river is impacted by other anthropic activities, such as dams, power plants, water diversion structures, deforestation, or pollution due to agriculture. The negative effects of gravel mining may not be immediately recognized due to the degree of resilience that each river systems holds (e.g., scour in bridges that can lead to collapse), but when the extractions exceed the natural replenishment for several years, the morphological consequences in terms of river incision may affect infrastructures in a way that becomes obvious to non-experts too. Scour phenomenon can be caused by many factors, such as excessive extraction of aggregates from the neighbouring riverbeds, and may cause structural problems to infrastructures located in the riverbed. For instance, Muñoz *et al*. (2009) assessed the cause of concrete bridges collapse in Colombia between 1986 to 2001, and found that 24% of them collapsed due to scour effects. More recently in Chile, the collapse of the Cancura bridge in the river Rahue (Los Lagos Region) in 2018 has been associated with excessive gravel extraction. Also, sediment extraction works in the Maipo River are in the spotlight of local communities since a heavy degradation of the river was reported by the *Dirección de Obras Hidráulicas* in 2015.

Chile is registering a rapid urban and industrial growth (the number of houses has increased in a 90% in the last 30 years; MINVU, 2021), which may increase the demand of aggregates, affecting those extractions from river systems. This has been traditionally associated to a lack of public opposition due to little awareness about the environmental effects of instream gravel activity. However, and despite the scientific literature on the topic is scarce in Chile, there has been an increase in environmental concern in the recent years, also in relation to the consequences of instream mining. This has been reflected in the news, raising knowledge and informing about the reports for illegal instream mining activities (see Supplementary material).

5.2. Adapting management proposals for instream mining in Chile

In the current legislation, the environmental evaluation of instream mining projects in Chile is only required when a certain volume of sediments is planned to be extracted (i.e. 400 m^3 per day or 50,000 m^3 in total). This threshold value is common for several rivers, and hence is not based on the nature of each individual river reach; i.e., bedload transport rates, sediment availability, sediment connectivity between generation areas and the channel. In fact, the criteria to authorise the volume of sediments to be extracted should be based on the characteristics of each river or river reach, according to an established criterion. One of the most used criteria is the consideration of a 'replenishment rate', i.e., limiting the annual extraction to the mean annual bedload supply from upstream, so that no more sediment is extracted than is supplied by the river (Kondolf *et al*., 2001). The application of this criteria requires the quantification of the bedload supply from upstream for each river reach where the instream gravel extractions are planned, as bedload transport rates are highly variable between rivers depending on the sediment grain size and physical characteristics of the basin and/or stream. Also, bedload supply is highly variable from year to year due to the intrinsic variability of the hydrology of the river, and because this process only occurs during high flows or floods, mainly in the latter. As ideally the long-term mean bedload transport value is commonly used as the limit to gravel extraction, the described high annual variability implies that the 'replenishment' of the hole/space caused by instream mining would not be achieved every year (Dunne *et al*., 1981). Furthermore, this approach does not prevent sediment deficit downstream from the mining site (Kondolf *et al*., 2001), since a negative sediment budget will occur, i.e., the sediment from upstream will replace the volume extracted at some point, but no (or less) sediments will be transported downstream, hence reducing the total volume being transported by the flow. It has been stated the importance of quantifying the natural bedload transport rates of rivers prior to the authorisation of instream gravel extractions. However, the number of scientific works assessing bedload transport is scarce for Chile. Only a few scientific articles have measured bedload transport in Chilean rivers, i.e. Martín-Vide *et al*., (2015) in the Toltén and Allipén rivers in the South, Carrillo and Mao (2020) in the Estero Morales in Central Chile, and Mao (2023) in the Silala river in the North of the country, while Pham Van and Chua (2020) used the data from the Toltén river to model bedload transport.

The issuing of permits for instream mining should not only consider the river reach where the sediments will be extracted, but also the other human activities being supported by the river system (i.e. watershed management plans, with a holistic view of the basins and their activities). Anthropic activities have an impact on the territory and their effects can accumulate, in the case of rivers from upstream to downstream. Hence, instream mining in rivers with other activities affecting sediment dynamics may exacerbate the impacts downstream. This could be the case, for instance, in a river basin with several river mining sites, or in rivers regulated by one or more dams.

Since the natural process of geomorphic adjustment may take many decades and even centuries to recover without human intervention (Booth *et al*., 2020), the law should include the obligation to restore the mining site and the affected river channel after the useful life of the project. The restoration or rehabilitation of the fluvial zone should consider both the active channel and the riparian zone, with a specific project for each river reach. These restoration actions need to be focused on river morphology creating a heterogeneity within the river and facilitating the development of riparian vegetation community based on native species. This can favour the recovery process and the functionality of the ecosystem. Consequently, both the riparian and instream habitat complexity may increase, which will favour the diversity of riparian and aquatic habitats and, therefore, the diversity of instream and riparian species (Hafs *et al*., 2014). As river restoration or rehabilitation should focus on riverine morphology, it is particularly important to consider their specific hydromorphological characteristics when designing the restoration plan. Indeed, Wyżga (2007) described some strategies for river restoration for reaches affected by instream gravel mining, which included the free formation of wood dams from fallen trees, or the free channel migration in erodible river corridors. Also, successful restoration plans in rivers affected by instream gravel mining included actions as, for instance, adjusting river slope and avoiding river steps, among others in the Johnsbach river in Austria (Rascher *et al.*, 2018), or modifying the geometry of the channel (i.e. widening and shallowing) in the Drac River in France (Brousse *et al.*, 2021). It is important to mention that the final result of the restoration action will depend on the hydrology and flood regime of the river. In any case, the information on the bedload sediment transport, channel geometry and hydraulics is essential to carry out successful restoration actions. In the case of Chile, this requires a profound effort to gather information and to characterise and classify Chilean rivers according to their physical characteristics. A decade ago, Andreoli *et al*. (2012) pointed out the need of a hydromorphological approach and the establishment of geomorphological standards for the management of Chilean rivers, since they are a main element for the assessment of their ecological state; i.e., sedimentary dynamic rivers usually have healthier aquatic and riparian ecosystems. Despite the warning of Andreoli *et al*. (2012), hydromorphological studies are mostly limited to research endeavour in Chile (e.g., Alcayaga *et al*., 2019; Elgueta *et al*., 2019; Ulloa *et al*., 2020). However, the importance of maintaining and promoting the good ecological status of rivers has been gaining importance in recent years, especially in society and among environmental researchers.

The planning of the human activities that take place in a territory is key to preventing the magnification of their impacts. River basin management plans are part of land-use planning, and analyse the area, identify its potentialities, pressures, and limitations, assess the interactions and/or potential conflict between activities, among others. Moreover, environmental protection and sustainability is gaining relevance in the land-use planning and could be a good opportunity to incorporate this perspective to the basin management plans. This would require a clear and organised institutional structure, with less institutions and no ovelapping between the ones that have some legal authority over river resources, i.e. not reproducing the current inefficient model that is established for water resources management, where several institutions have some kind of jurisdiction over water resources, with a lack of coordination between them (Rivera, 2021). Another issue that should be addressed is the consideration of river sediments as an essential part of the river, with relevant ecological implications since they are the support of the processes that take place in the ecosystem. To the knowledge of the authors, to date little or no attention is currently paid to these sediments, which may complicate the holistic consideration of the basin. Given that every river is unique and has its own characteristics and pressures, specific management plans for each individual basin could facilitate both the evaluation of instream mining projects and evaluate their viability according to the inherent characteristics of the river and the other anthropic activities in the territory.

6. Final remarks

In the recent years, there has been a growing interest on the preservation of natural ecosystems in Chile. However, fluvial systems have been widely degraded due to human activities for decades. Among them, instream sediment mining is one of the most detrimental activities in river systems and, although some countries have banned instream mining activities, Chile still has a high number of active instream mining sites, some of which are very large, i.e. affecting tens of kilometres and lasting for several years. This study mapped the instream sediment mining in Chile according to the SEA database. This database includes the projects that planned to extract large volumes of aggregates from the river and required an environmental evaluation, so it does not reflect the actual number of river mining sites, as only some extractions (based on the extracted volume of aggregates) must require this evaluation. According to the database, the central regions (i.e., Ñuble, Libertador Bernardo O'Higgins, Araucanía and Biobío regions) concentrate most of the projects in the country, a fact that could be expected according to river characteristics, such as their dimensions and gravel availability, and since most of the population concentrates in the urban areas of these regions.

Although regulation has been one of the most effective mechanisms for protecting the environment and its resources in many countries around the world, Chilean legislation is still working to achieve this. In fact, given the critical situation of Chilean rivers, this matter has recently been brought up for debate in the Chilean Senate. Lately, public awareness of river sediment mining activities has increased significantly, as evidenced by the number of articles and news stories published in the national press and blogs.

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Supplementary material

Examples of TV and newspaper news reflecting the society awareness of illegal instream aggregate mining and the associated impacts.

a) Channel T13: The municipalities of Quilpué and Viña del Mar reported illegal aggregate mining in Marga Marga stream on 04th September 2018. [https://www.youtube.com/watch?v=mpPntf8BUGo]

b) Hola Chile: On 24th May 2019, the Minister of National Assets of Chile, Felipe Ward Edwards informed of about 1000 ha of illegal aggregate mining in Chile, mainly in Metropolitan and Antofagasta regions. [https://www.youtube.com/watch?v=0F6At6sLxsw]

c) Channel T13: On 15th May 2019, T13 channel reported illegal extraction of sand in Metropolitan Region. [https://www.t13.cl/videos/nacional/video-reportaje-t13-aridos-ilegales-peligro-rio]

d) TVN (Televisión Nacional de Chile): On 11th October 2019, the 24 Horas TVN Chile reported illegal aggregates extraction in Putú, Maule Region. [https://www.youtube.com/watch?v=tC8E6zc5j0c]

e) Biobío Chile: The BioBío Radio reported, on 10th September 2024, an illegal aggregates extraction taking place during two decades from the Biobío River in Hualpén. [https://www.biobiochile.cl/noticias/nacional/region-del-bio-bio/2024/09/10/tridente-la-empresa-que-extrae-aridos-en-hualpen-y-que-funciona-sin-permisos-hace-casi-20-anos.shtml]

f) Biobío Chile: The Biobío Radio in 10th October 2024 reported illegal aggregates extraction from Biobío River. [https://www.biobiochile.cl/noticias/nacional/region-del-bio-bio/2024/10/10/concepcion-denuncian-extraccion-ilegal-de-aridos-del-rio-bio-bio-en-construccion-de-puente-industrial.shtml]

g) País Lobo: País Lobo reported, on 14th November 2024, an illegal extraction of aggregates in Osorno, Los Lagos Region. [https://www.paislobo.cl/2024/11/detectan-extraccion-ilegal-de-aridos-en-osorno-infractor-citado-tribunal.html#:~:text=En%20un%20patrullaje%20preventivo%20realizado,Ordenanza%20Municipal%20127%2C%20la%20cual]

h) Rengo en la Noticia Media: Rengo en la Noticia Media reported, on 2nd November 2023, that the Court ordered for stopping illegal aggregates extraction from Cachapoal River. [https://www.rengoenlanoticia.cl/not/2023/11/02/corte-de-rancagua-ordena-paralizar-extraccion-de-aridos-de-rio-cachapoal-y-envia-antecedentes-al-ministerio-publico/]