Universidad de Concepción
Dirección de Postgrado
Facultad de Ingeniería - Programa de Magister en Ciencias de la Ingeniería con mención en Ingeniería Civil

IN-STREAM MINING: SUPPORTING AND UNDERMINING CRITICAL INFRASTRUCTURE

(EXTRACCIÓN DE ÁRIDOS EN CAUCES: APOYO Y SOCAVACIÓN EN INFRAESTRUCTURAS CRÍTICAS)

Tesis para optar al grado de Magíster en Ciencias de la Ingeniería con Mención en Ingeniería Civil

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CONCEPCIÓN - CHILE
2019

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ABSTRACT

Sand and gravel mining are crucial to support massive construction and thus, countries development and economies. Best quality sand and gravel for construction are obtained from the riverbeds through in-stream mining. However, important geomorphological, hydrological, and ecological impacts of in-stream mining have been recognized. Importantly, river incision caused by sand and gravel extraction overlaps with local scour at bridge piers increasing bridges' failure risk. Are all in-stream mining activities dangerous for bridges? Is there a threshold mining volume that causes damage to bridges? How important to scour are the number of extractions around a bridge and what is the effect of the distance between a bridge and the mining pits? Are there management options to reduce bridge failures due to in-stream mining? In this thesis, we answer these questions based on results from a statistical analysis of the relationships between 379 in-stream mining activities and 30 bridges located over 10 major Chilean rivers, 21 bridges along 950 km of the Panamerican route between the cities of Santiago and Osorno. Obtained results show that: (1) scour at bridges is explained (>80%) by the extraction volume of the largest mining activity, (2) a large (>300.000 m^3/year) and single extraction is more damaging than several smaller extractions with the same total extraction volume, and (3) the distance between extraction and bridge affects bridge scour only in cases of large extraction volumes. Policies need to be urgently improved to allow river morphology to recover from in-stream mining and to avoid bridge damage. Regulation of the mining volume and rate, minimum distance between a bridge and a mining pit, and promotion of smaller activities distributed along the river, instead of big, localized mining is recommended.

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ACKNOWLEDGEMENTS

This work was funded by the Chilean research council CONICYT through project Fondecyt 1150997 Bridge pier scour under flood waves.

The author thanks Dr. Oscar Link for the support in the development of the thesis and the laboratory team for support and collaboration during field campaigns. Especial thanks go to Mr. René Iribarren.

The author also thanks her family and friends who were emotionally supporting this process.

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CHAPTER 1 INTRODUCTION

1.1 Motivation

Sand and gravel mining are crucial to support massive construction (Gavriletea, 2017), and thus countries development and their economies. Aggregate mining industry holds the biggest percentage in non-fuel mineral mining activities around the world (Menegaki & Kaliampakos, 2010), and sand became the most widely consumed natural resource on the planet after fresh water (Vilioth, 2014). The annual demand for construction aggregates was estimated to be about 3 x 10^9 tons in the US in 2006, and about 3 x 10^9 tons in Europe in 2011 (Podimata & Yannopoulos, 2016). In India, the yearly demand for sand is 23 million tons (Rege, 2016) and the annual world consumption of sand is estimated to be 15 billion tons, with a respective trade volume of 70 billion dollars (UNEP, 2014). A disbalance between sand and gravel availability in rivers and high demand leads to overexploitation and illegal mining. (Rege, 2016) estimated the illegal sand mining to be about 30% of the total exploitation in India.

Advantages in exploiting sand and gravel from in-stream mines instead of from other sources such as floodplains, include (Kondolf, 1994): (a) the material is already granulated, rounded, well-sorted, and generally clean (lacking cement and weak materials, and relatively free of interstitial fine sediment); (b) the source of material is generally close to destination or to the markets for the product, reducing transportation costs; (c) active channel sediments can be easily quarried (deep quarrying is not necessary), require little processing, and are periodically replaced from upstream during high flow events. Three types of in-stream sediment mining are distinguished (Kondolf, 1994; Rinaldi et al., 2005): (a) dry-pit mining, carried out on dry ephemeral stream channels with conventional bulldozers, scrapers and loaders; (b) wet-pit mining, below the water level on perennial streams, requiring the use of a dragline or a dredge; (c) bar skimming, consisting of scraping off the top layer (of variable thickness) from a gravel bar without excavating below the low water level.

Important geomorphological, hydrological, and ecological impacts of in-stream mining have been identified. A sediment deficit caused by in-stream mining typically induces upstream- and downstream-progressing river incision, lateral channel instability, change of channel pattern, bed armouring, and channel avulsion in the floodplain (Rinaldi et al., 2005; Luo et al., 2007; Martin-Vide et al., 2010).

In many countries, such as the UK, Germany, France, Holland and Switzerland, direct in-stream mining has been completely banned, while in other countries, such as Italy, Portugal, USA, Canada and Greece, it is allowed under restrictions (Kondolf, 1997; Gavriletea, 2017).

Existing regulations of in-stream mining set a minimum distance between the pit and bridges equal to 500 m in the Chilean case (DOH, 2019), or 1000 m in the Malaysian case (NRE, 2009). However, salient bridge failures caused by sand and/or gravel mining have occurred, such as the Hintze Ribeiro Bridge in Portugal in 2001 with 59 fatalities (Sousa & Bastos, 2013), the bridge over Phalguni river in India in 2018 (Misquith, 2018), and the study cases in California presented by Avila (2016). Sounding evidence shows that bridges frequently collapse in part due to the combined effect of general erosion – long term river incision due to in-stream mining, and short term general scour during floods (Ettmer et al., 2015) contraction and local scour (Hoffmans & Verheij, 1997).

Literature indicate that in-stream gravel mining activities cause bridge collapse, however, at the same time, all over the world a big amount of bridges that are exposed to these effects exhibit different degrees of damage, without collapsing. Are all in-stream mining activities dangerous for bridges? Is there a threshold mining volume that causes damage to bridges? How important to scour are the number of extractions around a bridge and what is the effect of distance between a bridge and the mining pits? Are there management options to reduce bridge failures due to in-stream mining? In this thesis, we answer these questions based on results from a statistical analysis of the relationships between 379 in-stream mining activities at 30 bridges.

1.2 Hypothesis

In-stream gravel mining increases scour at bridges, however, not all them cause infrastructure collapse. This effect can be controlled if management measures are implemented, such as the prohibition of gravel mining in-stream or establish a limit of gravel mining rate.

1.3 Objectives

1.3.1 General Objective

The general objective is to analyze the interaction between gravel mining in-stream and the undermining presented by the Panamerican bridges between Santiago and Osorno, and as well as measures for their control.

1.3.2 Specific Objectives

- Diagnose the scour of Panamerican bridges between Santiago and Osorno
- Determinate, through cadastre, in-stream gravel mining activities close of the bridges that could be affecting them.
- Determine the influence of variables that explain the scour bridges based on statistical regression model.

1.4 Methodology

To address the objectives of this research, the methodology was divided into three stages, where they are associated with specific objectives.

- Bridge scour diagnosis: Initially, the state of the bridges under study was evaluated, through the field campaigns. The scour at bridges was measured in 31 locations between Santiago and Osorno.

- Cadastre of aggregates extraction activities in rivers: In-stream gravel mining location and volumes were determined by project studies in the Environmental Impact Service (MMA, 2019) and the illegal in-stream gravel mining activities were determined by Google Earth.
- Determination of more influential variables: A multiple regression model was performed, including hydrological and in-stream gravel mining variables and, using statistical tools, the most influential variable in bridge scour was determined for the Chilean context.

1.5 Main results and conclusions

A multiple linear regression model was carried out to evaluate, through statistical tools, the main causes of channel degradation in Chile. For this purpose, a sample of 31 bridges was obtained, where the dependent variable was generalized degradation and the set of independent variables corresponded to hydrological and gravel mining variables in the study area. The main conclusion of this work were: (1) scour at bridges is explained (> 80%) by the extraction volume of the largest mining activity, (2) a large (> 300.000 m^3/year) and single extraction is more damaging than several smaller extractions with the same total extraction volume, and (3) the distance between extraction and bridge affects bridge scour only in cases of large extraction volumes.

1.6 Thesis structure

Chapter 1 presents the general problem to be investigated, working hypothesis, and general and specific goals, as well as an outline of the methodology. Chapter 2 present a review of the main theories and techniques related to the analysis of the relationship between scour at bridges and gravel mining in-stream. Chapter 3 describes the materials and methods, in particular the study site, measuring techniques and the multiple regression model used to determinate the most influential variables in scour at bridges. Chapter 4 presents the main results of the investigation. Finally, Chapter 5 concludes with final remarks on the obtained results and ways to proceed forward.

CHAPTER 2 STATE OF ARTS REVIEW

2.1 Introduction

This Chapter presents a brief literature review on the main effects of gravel mining in-stream in rivers and its relationship with scour at bridges.

2.2 Main effects of gravel mining in-stream

Rinaldi et al. (2005), Luo et al. (2007) and Martin-Vide et al. (2010) determined important geomorphological, hydrological, and ecological impacts of in-stream gravel mining have been identified. A sediment deficit caused by in-stream mining typically induces upstream- and downstream-progressing river incision, lateral channel instability, change of channel pattern, bed armouring, and channel avulsion in the floodplain The resulting incision alters the frequency of floodplain inundation along the river courses and lowers valley floor water tables (Rinaldi et al., 2005). Mining also results in the loss or impoverishment of aquatic and riparian habitats and other environmental impacts (Ashraf et al., 2011; Asabonga et al., 2017; Da Silva et al., 2018). Moreover, Freedman et al. (2013) showed that gravel mining alters diversity and structure of riverine fish assemblages. In many countries, such as England, Germany, France, Netherland and Switzerland, direct in-stream mining has been completely banned, while in other countries, such as Italy, Portugal, USA, Canada and Greece, it is allowed under restrictions (Kondolf, 1997; Gavriletea, 2017).

A mining pit in a riverbed is morphologically very unstable and subject to scouring and deposition, which results in migration of the pit (Lee et al.,1993.; Yanmaz & Ciceckdag, 2004; Barman et al., 2018; Barman et al., 2019). Surian and Rinaldi (2003) in Italian rivers, and WyZga (2007) in Polish Carpathian rivers reported channel incision due to in-stream mining with average values between 4 and 10 m. Arróspide et al. (2018) reported channel incision of up to 20 m between 1954 and 2015 in the Maipo river, Chile. Martín-Vide et al. (2010) proposed the diffusive model with a source/sink term to study the migration of several pits in the Gállego river, Spain over 42 years. In their model, the diffusion coefficient represented the river hydrology and was 0.045 m^2/s for the Gállego river.

2.3 Effect of gravel mining activities on the infraestructure

River degradation caused by sand and gravel extractions overlaps with local scour at bridge piers putting bridges at risk (Kondolf, 1997) due to a decrease of the bearing capacity, which commonly triggers the collapse (Chen et al., 2018). Bridge scour is a complex phenomenon, as it is governed by unsteady discharges and is temporarily countered rested by sediment deposition typically occurring during the falling limb of floods (Link et al., 2019).

2.4 Conclusion

The literature review determined a strong relationship between in-stream gravel mining and bridges scour and its important effects on rivers, mainly structures inserted in them. However, all over the world a big amount of bridges that are exposed to these effects exhibit different degrees of damage, without collapsing. The literature evidenced a lack of antecedents regarding the characteristic of in-stream gravel mining activities that cause further scour bridges and if these effects are related to hydrological variables.

CHAPTER 3 MATERIALS AND METHODS

3.1 Introduction

To understand the processes that influence the scour that affects main bridges of Chile, it is essential to know what the current state of the site under study is, emphasizing the characteristics of the basin and the gravel mining activities in-stream. In consideration of the above, this chapter collects hydrological attributes, gravel mining in-stream and the scour level that affects the bridges under study.

3.2 Study Area

The study area comprises 10 major watersheds of Chile (33°-34’54”) where the correlations between mining activities and 32 bridges were analyzed. Mining activities were considered when located at distances less than 40 km from a study bridge. Figure 1 shows the study area, bridges and mining activities and Figure 2 shows the study bridges.

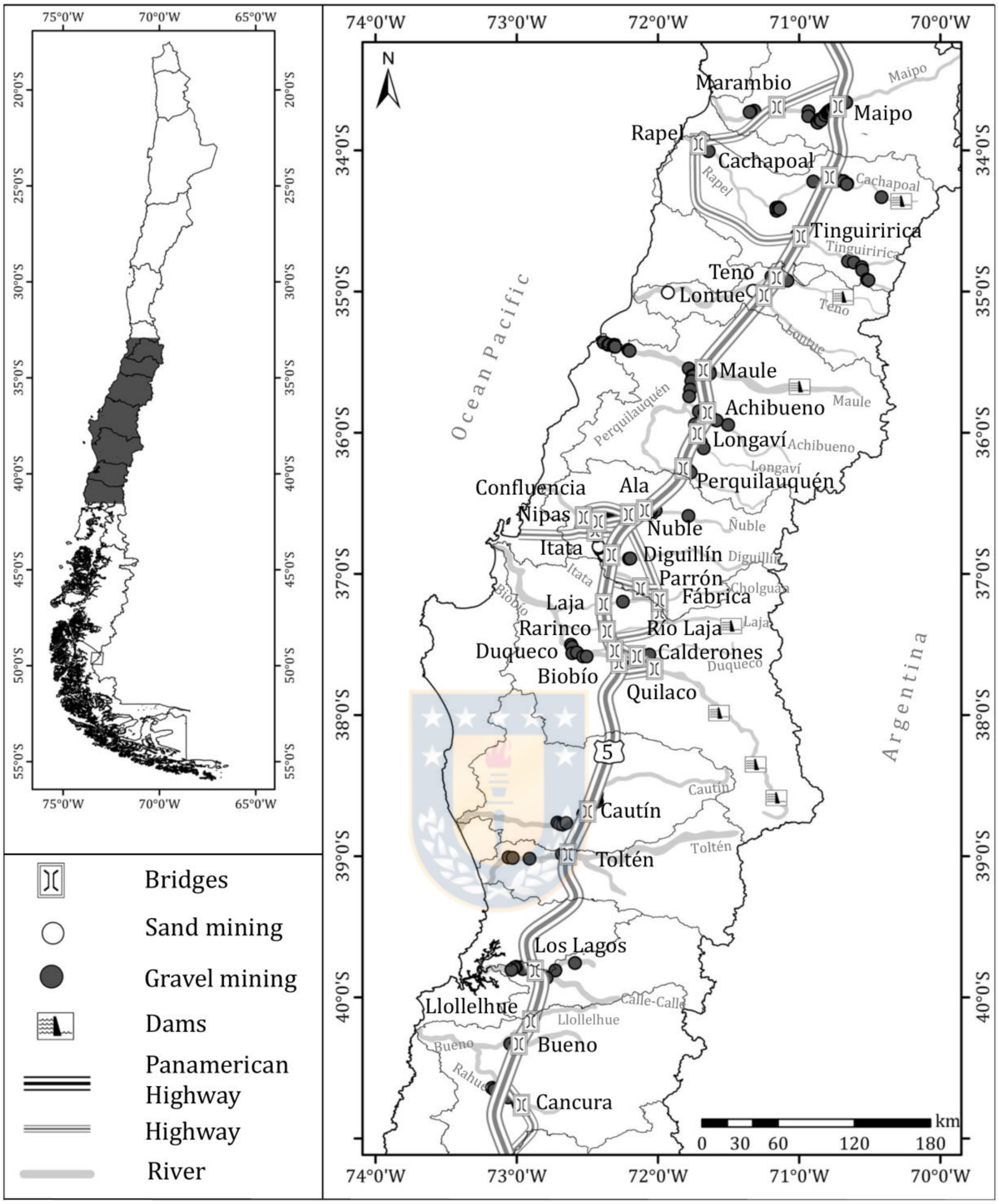

Figure 1. Location of the study area, bridges, and mining activities.

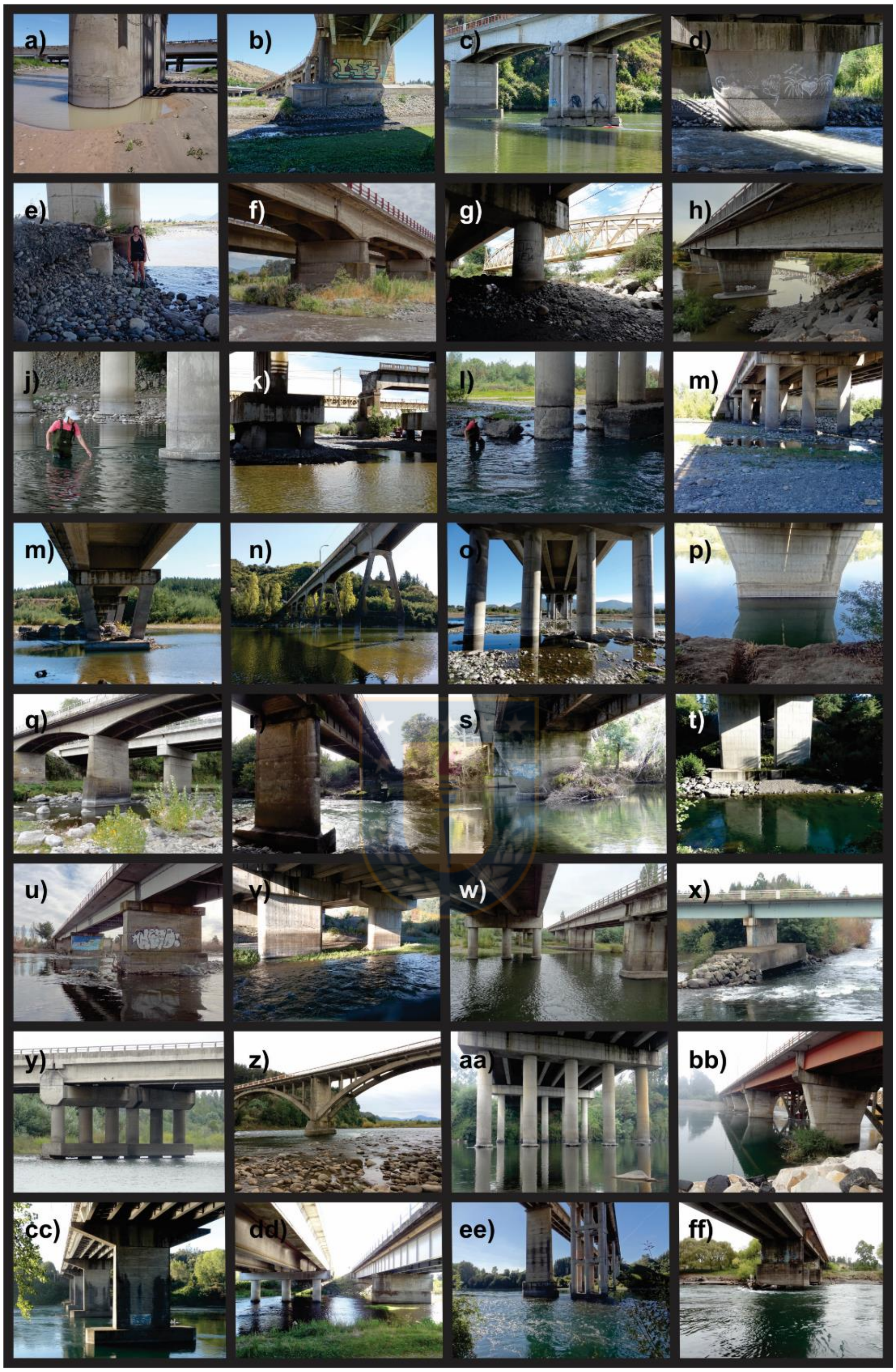

Figure 2 Photographs of the study bridges: a) Maipo, b) Marambio, c) Rapel, d) Tinguirirca, e) Cachapoal, f) Teno, g) Lontue, h) Maule, i) Achibueno, j) Longaví, k) Perquilauquén, l) Ñuble, m) Ala, n) Ñipas, o) Confluencia, p) Itata, q) Diguillín, r) Parrón, s) Fábrica, t) Laja, u) Río Laja, v) Rarinco, w) Duqueco, x) Calderones, y) Biobío, z) Quilaco, aa) Cautín, bb) Toltén, cc) Los Lagos, dd) Llollelhue, ee) Río Bueno, and ff) Cancura.

3.3 Characterization of bridge sites

Each bridge site was inspected during field surveys conducted between April, 2017 and August, 2018. The location was recorded with a field GPS (Garmin, Oregon 650). Information about the bridge construction year and original bridge drawings were obtained from the Archive of the Ministry of Public Works (MOP, 2017). At each site, the bridge geometry was measured using a measuring tape and a distance meter using long-sighted glasses. In the case of coarse sediments, the sieve curve of the riverbed was determined through the Wolman count technique (Wolman, 1954). In case of sandy sediments, the sieve curve was obtained by mechanical sieving in the laboratory following standard procedures (ASTM, 2017).

The watershed area at the study bridges was computed from SRTM satellite images (USGS, 2018) with spatial resolution 90 m using ArcGIS. Rivers' annual mean discharges were obtained from daily discharge records measured at gauge stations administered by the Chilean National Water Agency (DGA, 2018).

Scour at bridges was determined as the sum of observed riverbed degradation and local scour (Figure 3).

Figure 3 Inspection of a scoured bridge (a), observed riverbed degradation (b), and measuring local scour (c).

3.4 Characterization of in-stream mining activities around bridges

Locations of legal in-stream mining pits were obtained from the database of the Chilean Ministry of the Environment. This database includes only mining activities with annual extraction volumes > 100.000 m^3/year in Regions I-VIII, and > 50.000 m^3 in Regions VIII-XVII (MMA, 2019). Locations of smaller mining activities were obtained from the Ministry of Public Works (MOP, 2019). Locations of illegal in-stream mining pits were obtained from aerial photographs from GoogleEarth. Mining method, annual extraction volume and bed-load transport capacity corresponding to legal activities were obtained from MMA (2019) and MOP (2019). For illegal mining activities mining method and extraction volume were estimated from the size of the mining pit observed in the aerial photographs. Table 1 indicates the bridges' location, age, original drawings availability, watershed area, mean annual discharge, number of upstream dams and bed-load transport capacity.

Table 1 Properties of mining activities around the study bridges

Nr.	Bridge	Lat.	Lon.	Age	Original drawings	Pier diameter (m)	D_{50} (mm)	Watershed area (km^2)	Mean annual discharge (m^3/s)
1	Rapel	33°56'S	71°44'W	65	No	3	40	13697	171
2	Marambio	33°42'S	71°12'W	15	Yes	1.5	44	12065	92
3	Cachapoal	34°11'S	70°47'W	17	Yes	4.8	40	2925	37
4	Tinguiririca	34°37'S	70°59'W	32	Yes	4.8	53	1858	63
5	Teno	34°54'S	71°09'W	27	Yes	2	41	1462	64
6	Lontue	35°02'S	71°14'W	19	Yes	5.9	0.5	1877	79
7	Maule	35°33'S	71°41'W	26	Yes	3.5	70	6026	163
8	Achibueno	35°52'S	71°38'W	8	Yes	1.5	64	1421	64
9	Longaví	36°00'S	71°43'W	21	No	7	73	833	56
10	Perquilauquén	36°15'S	71°48'W	20	No	1.5	73	653	23
11	Ñuble	36°33'S	72°05'W	6	No	1.2	78	3001	132
12	Ala	36°34'S	72°12'W	23	No	1	83	3072	135
13	Confluencia	36°36'S	72°32'W	3	Yes	1.5	61	4789	170
14	Ñipas	36°38'S	72°26'W	95	No	0.7	0.5	9227	260
15	Itata	36°39'S	72°27'W	25	Yes	1.5	0.5	4298	121
16	Diguillín	36°52'S	72°19'W	52	Yes	1.6	88	1305	46

Table 2 Properties of mining activities around the study bridges

Nr.	Bridge	Lat.	Lon.	Age	Original drawings	Pier diameter (m)	D_{50} (mm)	Watershed area (km^2)	Mean annual discharge (m^3/s)
17	Parrón	37°06'S	72°07'W	68	Yes	0.6	0.5	882	32
18	Fábrica	37°11'S	71°59’W	38	Yes	0.5	72	507	26
19	Laja	37°13'S	72°23'W	10	Yes	3.5	0.5	2989	137
20	Río Laja	37°18'S	71°57'W	48	No	0.5	56	2757	112
21	Rarinco	37°24'S	72°22'W	18	Yes	14	37	275	11
22	Duqueco	37°32'S	72°19'W	16	No	1.5	72	1434	57
23	Calderones	37°35'S	72°09'W	44	Yes	8	50	1005	36
24	Biobío	37°36'S	72°17'W	15	No	1.5	50	7838	494
25	Quilaco	37°40'S	72°00'W	51	Yes	1	109	7599	416
26	Cautín	38°41'S	72°30'W	10	No	1.5	71	2702	131
27	Toltén	38°58'S	72°38'W	23	No	1	19	6092	581
28	Los Lagos	39°51'S	72°48'W	35	Yes	3	5	4644	530
29	Río Bueno	40°19'S	72°59'W	6	No	2	49	4275	377
30	Llollelhue	40°09'S	72°53'W	16	No	1.2	66	323	9
31	Cancura	40°45'S	72°58'W	40	Yes	3.7	71	1738	191

Table 1. Properties of mining activities around the study bridges (continued)

Nr	Bridge	Nr. of mining activities	Type of mining	Annual mining volume (m^3)	Dist. pit - bridge (km)	Bed-load capacity (m^3/year)	Upstream dams	Obs. scour depth (m)
1	Rapel	1	Gravel/Bar skimming	42,851	9.8	-	1	1
2	Marambio	18	Gravel/wet-pit	848,615	4.5	2,365,200	0	3.5
3	Cachapoal	7	Gravel/wet-pit	544,494	11.4	57,886,080	1	1.9
4	Tinguiririca	10	Gravel/wet-pit	268,402	1.4	15,345,000	0	0.7
5	Teno	4	Gravel/wet-pit	25,500	1.3	-	1	0.2
6	Lontue	3	Sand/wet-pit	86,875	3.3	-	0	0.9
7	Maule	15	Gravel/wet-pit	201,302	0.6	6,998,200	1	1.4
8	Achibueno	11	Gravel/ wet-pit	4,644	9.8	-	0	1.2
9	Longaví	6	Gravel/wet-pit	500,000	0.7	-	0	3.1
10	Perquilauquén	3	Gravel/wet-pit	74,023	2.9	-	0	0.7
11	Ñuble	27	Gravel/wet-pit	371,049	33.5	6,308,900	0	1
12	Ala	27	Gravel/wet-pit	371,049	21.5	6,308,900	0	0.9
13	Confluencia	26	Gravel/wet-pit	371,049	3.5	6.308,900	0	1.5
14	Ñipas	35	Sand/wet-pit	544,723	28.4	2,158,358	0	3.1
15	Itata	16	Sand/ wet-pit	404,013	17.7	2,158,358	0	1.7
16	Diguillín	7	Gravel/wet-pit	158,698	14.2	7,884,000	0	0.8

Table 1. Properties of mining activities around the study bridges (continued)

Nr	Bridge	Nr. of mining activities	Type of mining	Annual mining volume (m^3)	Dist. pit - bridge (km)	Bed-load capacity (m^3/year)	Upstream dams	Obs. scour depth (m)
17	Parrón	16	Sand/wet-pit	190,909	23.1	2,158,358	0	0.7
18	Fábrica	0	Gravel	0	0	-	0	0
19	Laja	7	Sand/ wet-pit	95,000	34.8	-	1	0
20	Río Laja	7	Gravel/wet-pit	240,000	12.1	-	1	1.2
21	Rarinco	0	Gravel	0	0	-	0	0
22	Duqueco	3	Gravel/wet-pit	30,000	17.7	-	0	0.7
23	Calderones	3	Gravel/wet-pit	300,000	0.3	-	0	3
24	Biobío	6	Gravel/wet-pit	245,454	1.6	6,550,000	3	1.7
25	Quilaco	6	Gravel/wet-pit	245,454	33	6,550,000	3	1.1
26	Cautín	5	Gravel/wet-pit	248,181	23.1	3,181,893	0	0.9
27	Toltén	5	Gravel/Bar skimming	458,182	40.7	-	0	0.7
28	Los Lagos	8	Gravel/Bar skimming	237,273	29	-	0	0.5
29	Río Bueno	3	Gravel/Bar skimming	65,455	0.5	-	0	0
30	Llollelhue	0	Gravel	0	0	-	0	0
31	Cancura	61	Gravel/wet-pit	1,170,000	0.5	2,835,633	0	3.6

3.5 Statistical analysis

One way analysis of variance (ANOVA) was used to find mining and bridge properties that explain observed scour. The multiple regression backward method with 95% confidence was applied. Variables were considered correlated when R^2>=0.6.

The agglomerative hierarchical analysis according to Ward (1963) was applied to detect multivariate similarities between the bridge sites through the software SPSS.

3.6 Conclusion

The study site was presented, as well as the measurement techniques used to perform the hydrological analysis in the area. The method used for the cadastre in the main extraction areas close to the bridges under study was also shown. Finally he statistical tool used to find bridge scour and in-stream gravel mining correlation, as well as to determine main influencing variables of degradation, ANOVA and Cluster Analysis, were presented.

CHAPTER 4 RESULTS

4.1 Introduction

This chapter shows and analyzes the results obtained from the relationship between the scour at bridges under study and the gravel mining that intervenes in their channels, interpreting through statistical tools the importance of each variable.

4.2 Results

Rivers and streams in the study area are middle size, with an average watershed area of 3,720 km^2 and mean annual discharges between nine and 581 m^3/s. Studied bridges are distributed along 950 km from North to South in a narrow strip of 25 m in width. Bridge ages range between three and 68 years with an average of 29 years. Original drawings indicating the original bed level at the bridge piers were available for 58% of the bridges. The pier diameters varied from 0.5 to 14 m, and the representative diameter of riverbed sediments ranged between 0.5 to 109 mm, with 13% bridge sites having sand beds and 87% having gravel beds. Table 1 shows the characterizing properties of mining activities around the 31 study bridges. Three of the 31 bridges presented no in-stream mining at a distance of 40 km up and downstream. On the other hand, the recently collapsed Cancura Bridge presented the most extractions, with 61 sites, followed by Ñipas Bridge with 35 extractions, and Ala and Ñuble Bridges with 27 extractions each. Of the extractions identified, 25% were close to the study bridges (5 km ratio) and 15% of them were illegal. Very large annual extraction volumes at almost all study sites were observed: 62% of the bridges presented extractions with more than 300.000 m^3 per year, with a maximum of 1.17 million of m^3 at Cancura Bridge. Eight of the 31 bridges were in river reaches with a dam upstream. Four bridges presented no scour, while the average observed scour was 1.2 m, with a maximum observed scour of 3.6 m at Cancura Bridge.

4.3 Relationships between scour and mining activities

Table 2 shows the goodness of fit statistics. For the 31 observations, the determination coefficient was 0.74 and the adjusted determination coefficient was 0.71, meaning that the model is not oversized. Correlation between variables is less than 0.2, which means that they are not correlated, i.e. they are independent variables.

Table 3 Goodness of fit statistics

Observations	31
DF	27
R^2	0.74
Adjusted R^2	0.71
MSE	0.31
RMSE	0.56

Table 3 shows the variance analysis. The sum of squares of the model is a large part of the corrected total, and thus the model explains much of the variance of the observations.

Table 4 Variance analysis

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	24.1	8.1	25.8	< 0.0001
Error	27	8.4	0.3		
Corrected Total	30	32.6			

Table 4 shows the standardized coefficients. The mining volume and the distance between the bridge and mining pit explain over 80% and 24% of the observed scour, respectively.

Table 5 Standardized coefficients

Source	Value	Std error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Mining volume (m^3)	8.1E-01	9.9E-02	8.2	< 0.0001	6.1E-01	1.0E+00
Dist. Pit- bridge (km)	-2.4E-01	1.0E-01	-2.4	2.5E-02	-4.4E-01	-3.2E-02

Figure 4 shows the observed over computed bridge scour using the maximum mining volume and the distance between the bridge and the pit as predictors. The central line corresponds to perfect agreement. Continuous grey lines indicate 5% confidence. Observed scour was correlated with the maximum mining volume, the distance between the largest pit and bridge, and the age of the bridge (ANOVA, F-test=25.75; p=0.0001). However, only the maximum mining volume and its distance to the bridge presented significant statistical correlation (Student's t-test <1.96; p>0.05). Clearly, a very good agreement between observed and computed scour is obtained (R^2=0.74). Primarily, bridge scour was controlled by the maximum mining volume.

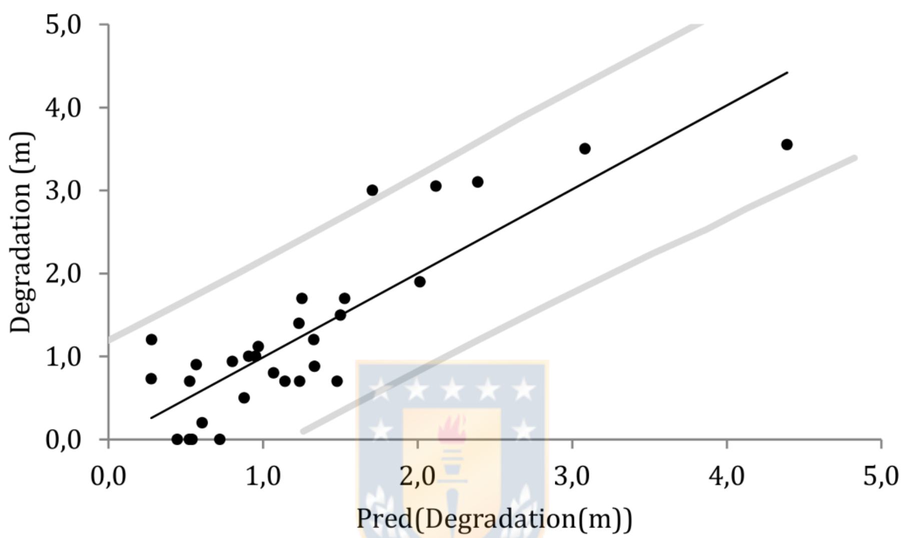

Figure 4 Observed over computed bridge scour using the maximum extraction volume and its distance to the bridge as predictors. Dotted central line corresponds to perfect agreement. Continuous grey lines indicate 5% confidence.

4.4 Analysis of bridge clusters

Five clusters were identified (ANOSIM, R_{global}=0.875, p=0.001). Table 5 shows the bridges in each cluster.

Cluster 1 was composed of bridges with high scour and high mining volumes. Cluster 2 was composed of the most common bridge situations, typically gravel bed rivers, average slope, and average mining volume. Cluster 3 is composed by typical sand bed rivers. Cluster 4 includes only one bridge in a rare situation as it present mining activity but no scour. Cluster 5 is composed by bridges with comparatively small scour.

4.5 Conclusion

The results obtained from the study were presented. The main variables that explain the scour at bridges in Chile, the largest volume of extraction in the river by gravel mining activities (> 80%) and the distance of that from the bridge (> 20%). This also indicates that the distance between gravel mining pit and the bridge only contributes to scour at bridges in cases of large extraction volumes.

CHAPTER 5 Conclusions and Discussion

5.1 Discussion

In-stream mining supports national economic growth based on the construction of infrastructure, importantly roads and bridges, but at the same time contributes towards putting critical infrastructure at increasing risk. Regarding illegal sand and gravel mining, smaller economies such as Chile present a similar situation to those of European countries (Podimata & Yannopoulos, 2016), USA, and India (Rege, 2016). For example, according to the Chilean Ministry of the Environment (MMA 2019), 245 legal sand and gravel exploitation projects started in Chile between 1997 and 2019, and some of them will run until 2030, totalizing an annual volume of 9.5 millions m^3 in 2019, with a growing rate of about 1% for the period. 52% of the total legal annual volume corresponds to in-stream sand or gravel mining. At the same time, from concrete production estimates by the Chilean Construction Chamber (CChC 2019) it follows that at least 15 millions m^3 of sand and gravel are currently demanded for concrete, and thus similarly to India, about 30% of the Chilean annual production of sand and gravel is estimated to be illegal.

Sounding evidence shows that bridges collapse all over the world due to scour (Brandimarte et al., 2012; Proske, 2018) which is the superposition of long-term general erosion, i.e. river incision, short term channel bed degradation during floods, and local scour at piers and abutments. In-stream mining causes severe river incision (e.g., Surian & Rinaldi, 2003; WyZga, 2007; Arróspide et al., 2018) and all over the world a big amount of bridges have been exposed to these effects for long periods of time, exhibiting different degrees of scour from negligible to severe, but without collapsing (Briaud et al., 2013). Unfortunately, until now, there are no general formulas to estimate the speed of mining pit propagation, and corresponding incision depth for a given river (Martin-Vide et al., 2010). The best practical solution to control riverbed incision is the construction of a bed sill downstream of the bridge cross-section to provoke sediment deposition upstream (Comiti et al., 2005; Martín-Vide & Andreatta, 2006; Almeida & Martín-Vide, 2011; Su & Lu, 2013).

However, difficulties appear in torrential rivers, as the bed sill typically collapses during extreme floods, i.e. when the river flow has the maximum scour capacity. We analyzed 31 bridge sites with different scour (0 – 3.3 m) exposed to in-stream mining activities located between 40 km upstream and 40 km downstream of the bridge section. 45% of the bridges were exposed to the effects of large extractions of over 300.000 m^3/year. Gravel mining was mostly performed through bar skimming (13% of the study sites), but contrarily to recommendations (NRE, 2009), extractions took place at deeper levels than the so-called red-line, generating large excavation pits, especially in case of illegal extractions. Mostly, the excavation of in-stream gravel pits was done with backhoe loaders using deeper extension arms to reach up to 10 m in depth. Sand pits, instead, were typically generated with draglines achieving depths of over 16 m. Our results showed that observed bridge scour is primarily explained by the maximum sand and gravel mining volume occurring between 40 km upstream to 40 km downstream the bridge. The distance between the biggest mining pit and the bridge was important for scour only in case of large mining volumes, i.e. volumes greater than 300.000 m^3/year. These relationships might change for bridge sites located in river reaches with different climatic and geological controls. In the studied cases, longitudinal bed slope was always high (in the range of ~0.1-1.0 %), and according to the Köppen climate classification (Beck et al. 2016) the watersheds are characterized by a warm-summer Mediterranean climate (Csb) with well-defined seasons. Following the diffusive model introduced by Martín-Vide et al. (2010), we expect that the diffusion constant was high and similar in all studied cases, explaining why distance didn’t play a major role explaining observed scour. Consequently, the regulation of the minimum distance between in-stream excavation and bridges (e.g. tween 150 and 3000 m in Chile, depending on the commune, or 1000 m in Malaysia) might be useful only in combination of a regulated mining volume and rate.

Large, single extractions caused more bridge scour than several smaller extractions with the same volume, in agreement with the experimental study of Haghnazar et al. (2019). For example, bridges Laja and Diguillín, presented low scour of 0 and 0.8 m, respectively, with corresponding maximum extraction volumes of 1.5 and 3.0 million m^3/year, while bridges Maule and Calderones presented moderate and severe scour of 1.4 and 3.0 m, respectively, with corresponding maximum extraction volumes of 2.0 and 3.0 million m^3/year, respectively.

Local regulations of in-stream sand and gravel mining need to be urgently improved to allow river morphology to recover from extractions and to avoid further bridge damage. In particular, our results suggest that the following management measures would contribute to diminishing risk of bridge collapses: a) regulation of the mining volume and rate around bridge sites according to the real (not potential) sediment reposition rate of the specific river reach and to the local morphology of bars, avoiding excavations below the average bed level dictated by the average longitudinal reach slope, b) regulation of the minimum distance between a bridge and a mining pit, and c) promotion of mining through several small activities distributed along the river instead of big, localized ones. In this context, seasonal measurement of bed-load transport for accurate estimation of the actual reposition rates, and monitoring of river bed levels during mining should be mandatory.

5.2 Conclusions

A statistical analysis of the relationships between in-stream mining activities and 31 bridges located over 10 major Chilean rivers, 21 of them along 950 km of the Panamericana route between the cities of Santiago and Osorno, was presented. Results showed that scour at bridges is explained (> 80%) by the largest mining volume, a large (> 300.000 m^3/year), single mining activity is more damaging than several smaller activities with the same total extraction volume, and the distance between bridge and mining pit affects scour only in cases of large mining volumes. In consequence, we recommend the development of policies for regulation of the mining volume and rate around bridge sites, regulation of the minimum distance between a bridge and a mining pit, and to promote the mining of riverbed sediments through several small activities distributed along the river, instead of big, localized activities.

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