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Morphological evolution of the Maipo River in central Chile: Influence of instream gravel mining

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ABSTRACT

Instream gravel mining is one of the most important causes of channel degradation in South America, specifically in rivers located near large metropolitan areas with rapidly growing cities, where no river management strategies exist. In the western region of the continent, many of these rivers belong to Andean systems, in which significant parts of the watersheds are located in mountain areas at high altitude, with considerable seasonal rainfall variability and steep channel slopes. In these rivers, gravel mining has produced significant incision of the channels with serious physical and ecological consequences, affecting habitats, modifying the supply and transport of sediments, and amplifying the risk to infrastructure in and around the channel during floods. In spite of the degraded conditions of many channels, no quantitative studies of the geomorphic impacts of gravel mining have been carried out in the region, mostly because of the insufficient and sparse data available. In this investigation we perform an analysis of the morphodynamic evolution in a section of the Maipo River in the metropolitan region of Santiago, Chile. This river is economically the most important in the country, as it provides drinking and irrigation water to urban and rural areas, is utilized by the energy generation industry, and runs along and below critical infrastructure. We have collected and analyzed data from 1954 to 2015, during which the city population increased by more than 5 million inhabitants whose presence accelerated land use changes. The analysis shows a rapid morphological evolution of the channel where in 31 years effects such as: river sections showing incision of up to 20 m, an increase of the area affected by gravel mining from 86.62 to 368.13 ha, and a net erosion volume of 39.4 million m^3 can be observed. This work yields quantitative information on the consequences of gravel mining in the Maipo River, providing the necessary data to develop an integrated strategy to define management and restoration actions for this and other similar Andean rivers.

1. Introduction

Human activities can impact significantly the morphology of rivers by modifying the supply, transport, and storage of sediments in the watershed. These alterations to the sediment regime not only affect the morphological evolution of the river channel but can also endanger the infrastructure and ecological integrity of the streams by disturbing the stability of the channels, increasing bank erosion, and modifying the aquatic habitats in the river (Kondolf, 1994b; Surian and Rinaldi, 2003; Comiti et al., 2011).

Instream gravel mining is one of the most detrimental activities in the evolution of the river morphology and has significant consequences over spatial and time scales, from tens of years (Petit et al., 1996; Rinaldi et al., 2005; Arnaud et al., 2015) to hundreds of years (Surian and Rinaldi, 2003; Comiti et al., 2011; WyŻga et al., 2016). Effects of gravel mining have been widely studied in Europe and North America (Kondolf, 1994a; Kondolf, 1994b; Gaillot and Piégay, 1999; Martín-Vide et al., 2010; Comiti et al., 2011; Ziliani and Surian, 2012). In Italy and Spain, for example, gravel mining has been identified as the main driver in river adjustments (Batalla, 2003; Surian et al., 2009; Scorpio and Rosskopf, 2016), which acts together with additional processes linked to channelization and afforestation, along with the presence of dams, that might also have greater predominance on channel evolution (Kondolf et al., 2007; Warner, 2012). In France, gravel mining in coastal rivers has produced beach erosion (Gaillot and Piégay, 1999), and dams have had a significant

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effect on river morphology by favoring sand harvesting and yielding water table and riverbed lowering as direct effects (Petit et al., 1996). In Poland, extraction of coarse particles in the riverbed favored the entrainment of finer material (Zawiejska et al., 2015) and channel incision had different effects on rivers depending on their stream power and also with different effects at the local or regional scale (WyŻga et al., 2016).

Although effects of sediment mining on rivers may be different depending on the degree of human intervention, clearly the temporal relationship is strong with rivers being highly responsive to human impact and even showing the occurrence of 'inertial' effects (Surian and Rinaldi, 2003; Rivas et al., 2006; Martín-Vide et al., 2010; Belletti et al., 2016) and the capability to recover when human activities stopped at the river (Comiti et al., 2011; Scorpio and Rosskopf, 2016).

To study these effects and understand the current and long-term conditions, a historical analysis on river morphology can be performed to evaluate quantitatively evolution of the channel. Planform analysis has been performed throughout the years by the use of maps and air photographs (Downward et al., 1994; Gurnell et al., 1994; Hughes et al., 2006; Zanoni et al., 2008; Comiti et al., 2011; Little et al., 2013; Arnaud et al., 2015). These remote sensing techniques have proven to be quite accurate measuring landscape properties (Mertes, 2002). Studies of morphological changes have examined adjustment of the active corridor width and land cover (Zanoni et al., 2008; Comiti et al., 2011), active channels (Comiti et al., 2011; Arnaud et al., 2015), and vegetation boundaries (Comiti et al., 2011; Arnaud et al., 2015). Cross section topographic sampling and analysis has also been used to estimate sediment budget, incision, or deposition (Gob et al., 2005; Arnaud et al., 2015). Technological improvements have allowed the use of digital elevation models (DEMs) to directly calculate sediment budgets (Lane et al., 2003; Wheaton et al., 2010; Milan et al., 2011; James et al., 2012). These DEMs are constructed upon digital photogrammetry, laser altimetry, and image processing to provide a complement for cross section analysis as the comparison of DEMs requires an error filter (Milan et al., 2011).

Rivers in Europe have shown a common pattern of evolution of their morphology (Surian and Rinaldi, 2003; Surian and Rinaldi, 2004; Surian et al., 2009; Scorpio et al., 2015; Scorpio and Rosskopf, 2016) in the last 150–200 years, with incision and narrowing of channels as the main processes at the initial stages from the early nineteenth century to the 1980s–1990s(with the most intense period being between the 1950s to 1990s) followed by a widening and sedimentation phase afterward. Sediment mining and dam construction have had a main role in the incision and narrowing phases with an intense effect at the beginning and then becoming slower toward the asymptotic state.

The incision process has been observed to be closely tied with gravel mining and vice-versa (Kondolf, 1997), with average values of riverbed incision in the order of 4 to 10 m (Surian and Rinaldi, 2003; WyŻga, 2007), and in some cases, incision has been persistent even though mining operations have stopped (Surian et al., 2009; Martín-Vide et al., 2010; Comiti et al., 2011), evidencing the 'inertial' effects. Narrowing has been observed in the active channel for braided rivers to an order of 50% (Surian and Rinaldi, 2003), changing the pattern to a wandering one. However, experiences show that once gravel mining stops, the active channel starts widening again (Comiti et al., 2011). Although most cases have experienced incision alongside narrowing, exceptions exist where incision and widening have taken place concurrently (Bollati et al., 2014).

In this context, South American studies on river morphology and its evolution through time are currently under development, with research performed in Argentina where the intensity of changes in rivers are driven mainly by the combination of technology, wealth, and growing urban population (Rivas et al., 2006); however, no additional studies have been performed. In addition to the accelerated urban expansion and changes in land use and cover, many rivers in developing countries are also affected by instream gravel mining, which is one of the most important disturbances, producing rapid incision and narrowing of the channels. In South America, most of the urban growth has occurred in mountainous regions or the piedmont near the Andes, where the rivers have been impacted by (besides gravel mining) the construction of dams, power plants, water diversion structures, and deforestation. Such is the case of Chile, where the local scientific society has already noted the need for a hydromorphological approach on river management (Andreoli et al., 2012) and methodologies for optimization of exploitation of resources have been proposed (Godoy et al., 2010); however, quantitative studies are scarce, and most scientific evidence is available locally, trying to adapt analyses performed in other latitudes to the local context.

Our investigation is the first of its kind in South America to provide quantitative measurements of morphological impacts caused by instream human activity, with gravel mining being the most important. Our goal is that this paper will become a first step toward increasing attention on Chilean and South American fluvial systems in an integrated management focus.

This paper is organized as follows. In Section 2 a brief description of the area of study, the Maipo watershed in central Chile is presented, including the sub reach where most of the gravel-mining activities have concentrated. The methods employed in this investigation, including the available data, are explained in Section 3. In Section 4, evolution of the Maipo River through the calculation of morphological parameters is reported. In Section 5 the relation among these parameters and the consequences of instream gravel mining is discussed. Finally, the conclusions summarize the findings of this investigation and outline topics for future research.

2. Study area

The study was carried out in the Maipo River basin, draining an area of 15,380 km^2, most of it located within the metropolitan region in central Chile, between 32°55′–34°15′ S and 69°46′–71°43′ W (Fig. 1). The river headwaters lie at the foothills of the Maipo Volcano (3135 m a.s.l.) in the Andes mountain range. Most drinking water and irrigation supply in the region is provided by the Maipo River, ~70% and 90% respectively.

The climate is Mediterranean with an extended dry season, although recent studies show a warming trend in the central valleys of Chile (Cortés et al., 2011). The dry season starts in April and ends in October, which corresponds to autumn and winter. During spring and summer, the snow melting in the Andes raises the discharge in the Maipo River and its tributaries, making the river especially sensitive and dependent on snowmelt for irrigation purposes (Cortés et al., 2011). Historical monthly average flow is 104 m^3/s, while the snowmelt season (October to March) average discharge is 151 m^3/s and during winter (April to September) has an average month discharge of 57 m^3/s, showing an ~50% variability. Fig. 2 shows the day average river discharge.

The Maipo River is a key element for the basin and the city of Santiago, as it has been directly involved in major events that have caused significant effects on the cities and local towns, mainly debris flows and water supply interruption for millions of inhabitants from 2008 to 2017 (e.g., Sernageomin, 2016). The water supply system is subject to a high risk of failure because of increasing turbidity caused by warm storms in the Andes region. Warm storms raise the freezing level in the ravines and foothills of the Andes mountain range increasing the water volume available causing flooding, landslides, and debris flows if precipitation is intense or prolonged (Garreaud, 2013). Every time these phenomena take place, drinking water supply is completely halted for most of the city of Santiago, affecting