PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE
ESCUELA DE INGENIERÍA

MORPHOLOGICAL EVOLUTION OF THE MAIPO RIVER IN CENTRAL CHILE: INFLUENCE OF IN-STREAM GRAVEL MINING

FELIPE ANTONIO ARRÓSPIDE ALARCÓN

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:
CRISTIÁN ESCAURIAZA MESA

Co-Advisor:
LUCA MAO

Santiago de Chile, July 2017

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Members of the Committee:
CRISTIÁN ESCAURIAZA MESA
LUCA MAO
SEBASTIÁN VICUÑA DÍAZ
PATRICIO MORENO CASAS
MIGUEL TORRES TORRITI

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Gratefully to my parents and sister, Marco Arróspide, Cecilia Alarcón and María Ignacia Arróspide, who have always believed in me. And to Mosquito Ulo Ulo, the greatest inspiration of all mankind.

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ABSTRACT

Human activities in rivers such as dams, irrigation and gravel mining may affect their morphology. This last one, has been identified by literature to be one of the most influencing of all. This research focuses on a portion of the Maipo river (Chile), identified as one of the most intervened by gravel mining. By using historical maps, air photographs, topography and digital elevation models, morphological changes due to human intervention for the last 60 years are measured and assessed. Results show an increase on gravel mining area by 320%, along with a descent on the bed level (incision) and a general channel narrowing, reducing the braiding index on the river. Net lost volume was calculated to be around 39 million of m^3 between 1980 and 2011. These results are consistent with those exhibited in the available literature and represent a first step in South America for hydromorphological studies towards the design of river management strategies in the future.

Keywords: river morphology, geomorphology, gravel mining, human impact, satellite images, channel narrowing, Chile, Maipo.

RESUMEN

La actividad humana en los ríos, puede afectar la morfología de éstos, con intervenciones tales como represas, irrigación y la extracción de áridos. Esta última, identificada por la literatura como una de las actividades con mayor impacto en los ríos. Esta investigación se centra en una porción del río Maipo (Chile), identificada como la más afectada por intervención humana, especialmente por extracción de áridos. Utilizando mapas históricos, fotografías aéreas, topografía y modelos de elevación digital, se miden y evalúan los cambios morfológicos debido a la acción humana en el río en los últimos 60 años. Los resultados muestran un aumento un 320% de la superficie de extracción de áridos, en conjunto con un aumento en la profundidad del lecho del río (incisión) y un estrechamiento general del ancho del río, derivando en una disminución del grado de trenzado del río, similar a lo registrado en la literatura. Se calculó el volumen neto de material extraído en el río en 39 millones de m^3 entre 1980 y 2011. Estos resultados se muestran en concordancia con la literatura disponible y representan un primer paso en Sudamérica para los estudios hidromorfológicos y la elaboración de planes de gestión de cauces a futuro.

Palabras Claves: hidromorfología, geomorfología, extracción de áridos, impacto antrópico, imágenes satelitales, estrechamiento de ríos, Chile, Maipo.

1. INTRODUCTION

1.1. Motivation

In a context of a dynamic urban development throughout the major cities in the world, where current reports show that urban population represents around 54% of the total inhabitants, showing a significant growth from the first half of the 20th century where 30% of it was urban. Latest estimates show that by 2050, 66% of the world population will be located in urban areas (Nations, 2014). These same situations can be seen for worldwide water resources withdrawal (Figure 1.1), showing that in the course of a century, water withdrawal has increased eight times, from 500 km^3/year to 8000 km^3/year. This fact implies an increase on the water demand from the urban systems, which in turn will affect the dynamics of rivers, streams, lakes, reservoirs and water systems in general. It even has been estimated that global population change and economic development will have more influence over the water supply and demand system than climate change (Vorosmarty, Green, Salisbury, & Lammers, 2000).

For this reason, water resources management will be of great importance, since rivers from urban basins (impacted by human activities) will suffer greater changes than unimpacted basins (Palmer et al., 2008) and therefore, more stress and conflict over the water resources will take place between stakeholders, communities and society within these basins (Poff et al., 2003). The scientific community has already addressed the need for an effective river management in order to minimize the risks and impacts of climate change and population growth (Alcamo et al., 2003; Andreoli et al., 2012; Gleick, 1998; Palmer et al., 2008), taking into account the multiple spatial scales involved and possible future scenarios (Allan, Erickson, & Fay, 1997; Arnell, 1999).

In order to understand the dynamics of intervened river systems and propose management strategies, morphologic characterization of rivers is essential for analysis, allowing the identification of shapes, patterns and features at different spatial and temporal scales.

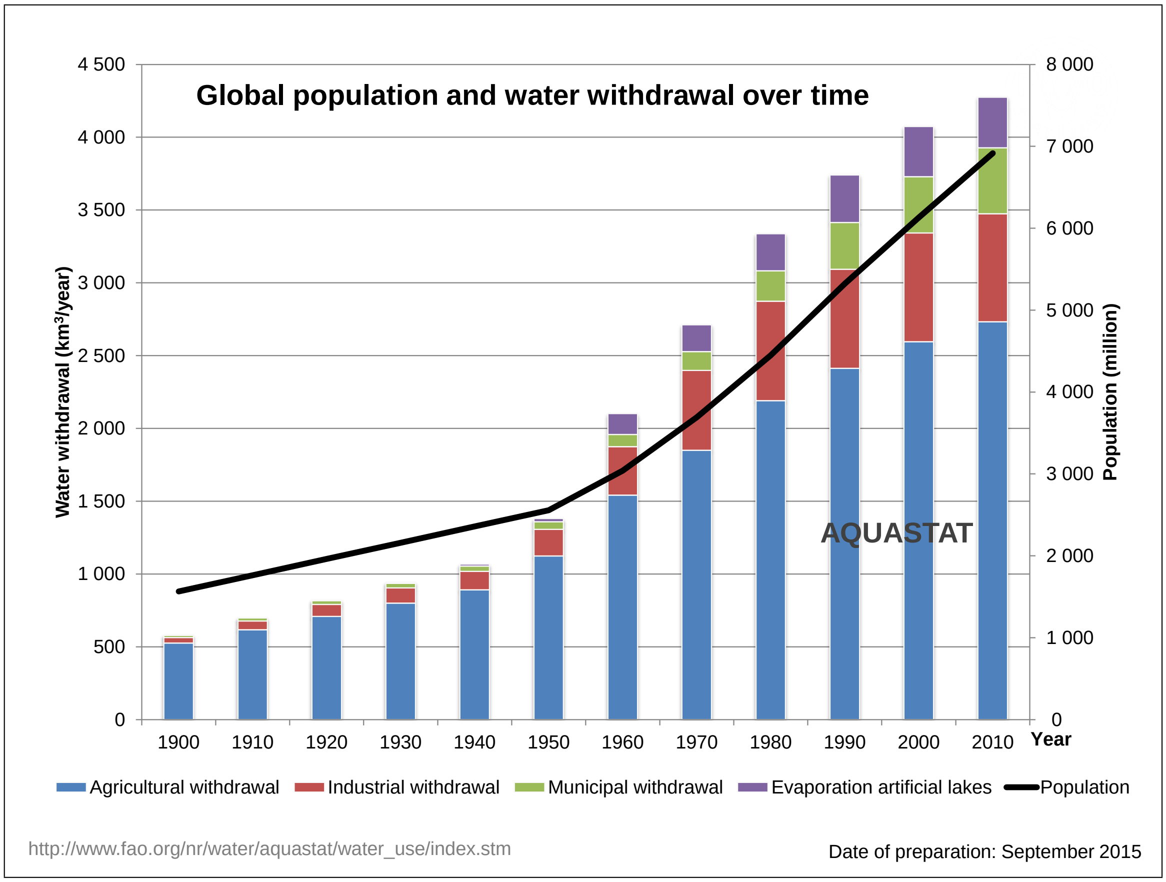


Figure 1.1. Worldwide water withdrawal use, from (FAO, 2016).

This approach has been used since the 1980s, showing different approaches, methodologies, procedures and materials (Belletti et al., 2017; Biron et al., 2014; Downward, Gurnell, & Brookes, 1994; Gregory, Benito, & Downs, 2008; James, Hodgson, Ghoshal, & Latiolais, 2012; Kondolf & Larson, 1995; Lane, Westaway, & Hicks, 2003; Rinaldi, Surian, Comiti, & Bussettini, 2015)

1.2. Human Intervention in Rivers

In this investigation the researchers focus on river intervention, where plenty of experience and study cases can be found in Europe and in the USA regarding to antropic activities in rivers and subsequent actions taken to allow river restoration. For example in italian rivers (Comiti et al., 2011; Rinaldi, Wyzga, & Surian, 2005; Scorpio et al., 2015;

Scorpio & Rosskopf, 2016; Surian & Rinaldi, 2003, 2004), where gravel mining activities have been identified as one of the main drivers of river evolution in time. This same conclusion is found in polish rivers (Wyzga, 2007; Wyzga, B., Zawiejska, J., Radecki-Pawlik, 2014). It has been found that in-channel mining commonly causes incision, which may propagate up-and downstream of the mine, undermining bridges, inducing channel instability and lowering alluvial water tables (Kondolf, 1997). The removal of sediment from a channel caused by gravel mining, disrupts de preexisting balance between sediment supply and transporting capacity. Excavation of pits in the active channel alters the equilibrium profile of the streambed, creating a local gradient (as shown in Fig. 1.2). This mining induced incision may propagate upstream on the river, or even up tributaries (Kondolf, 1994b). With continued extraction, the bed may degrade down to bedrock or older substrates. Other problems such as loss of vegetation due to lower bed elevation and therefore no overbank flow are also related to gravel mining.

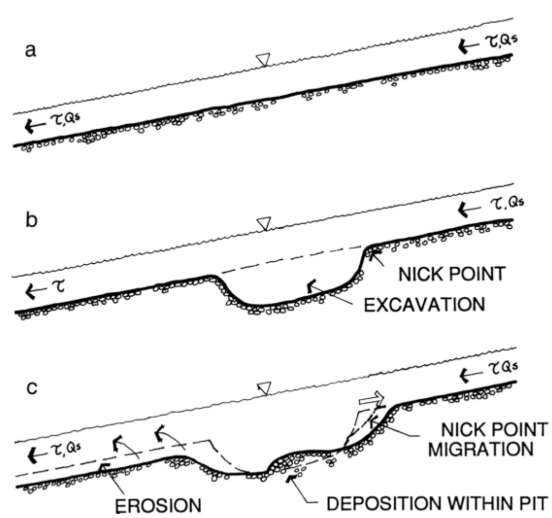


Figure 1.2. Incision produced by instream gravel mining, by Kondolf (1994b).

Although human impact on rivers has been studied and documented widely in Europe, the US and Canada, this topic is relatively new to developing countries such as Chile, where local studies regarding this topic are scarce and most of them focus on aquatic habitat (Andreoli et al., 2012). This may be due to the fact that developing countries still do not face water scarcity issues or excessive stress of their water systems in contrast to first-world countries, but their population growth will trigger these issues in the next 25 to 50 years (Alcamo et al., 2003; Arnell, 1999).

1.3. River Intervention in Chile: The case of the Maipo river

In Chile, most natural channels and rivers are born in the Cordillera de los Andes mountain range. These rivers flow mainly from east to west, passing by major cities and towns. The transverse extension of chilean rivers allow them to be exploited by the population in several ways, depending on the specific zone, morphology and hydrology of the stream. Some of the uses are listed as follows:

- Gravel Mining.
- Irrigation.
- Upstream water storage in dams for public drinking use or hydroelectric power generation.
- Public recreation.
- Downstream waste dump by local residential areas and/or industries.
- Infrastructure support.

In this study, the focus is set on the Metropolitan Region, where the capital city of Chile, Santiago, lies. The main river of Santiago is the Maipo river, which makes it one of the most important in the country. It flows through the south of Santiago, one of the most populated areas of the city.

The Maipo river shows all the activities listed previously, being gravel mining, drinkable water supply, irrigation and infrastructure the most important ones. This gives the river a great economical relevance, since it is indirectly used by an important percentage

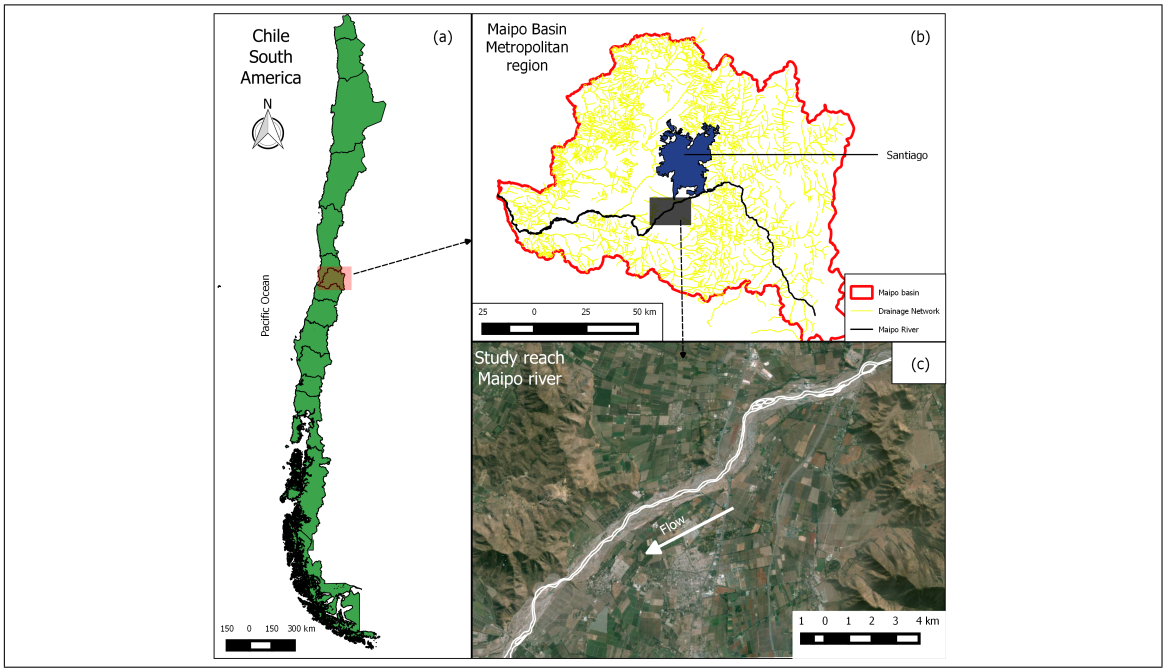


Figure 1.3. Location of the Maipo river in Chile. The river flows from east to west and is located south of Santiago.

of the total population of the country. Therefore, the potential economic detriment comes in hand with the potential risk of natural disasters occuring on the river.

Even though the Maipo river is one of the most importants rivers in Chile, it lacks of a clear organisation and capability of self sustaining. This fact is given by the wide variety of stakeholders within the river and their own interests which differ from one to another (Ocampo-Melgar, Vicuña, Gironás, Varady, & Scott, 2016). Many attempts to establish regulations have been made alongside with "Master Plans" which serve as guidelines for the management of the river, however with no laws or rules to support these, the effect they have is shallow.

In the next section, the current status of the Maipo river is explained, in order to set the goals of this investigation, identify possible limitations and define the outline of the main task to be performed.

1.4. Current situation of the Maipo river

In year 2009 the Maipo river went under a thorough analysis on a macro scale. Several conflictive situations have been identified in the last technical report (Consultores, 2009), such as river bank overflow, accumulated garbage, flooding in populated areas, gravel mining in improper locations, damaged bridges and intensive erosion near populated areas (some examples in Figs. 1.4 and 1.5).

Of these situations, the higher risk lies in the scour of the bridges foundations, which may render the bridges not operational. The presence of heavy gravel mining may change the river morphology to a degree that could change the river responde to floods coming from the Andes, however these effects are not studied in detail in 2009.

The 2009 study identified approximately 55 different gravel mining companies located in the Maipo river, with an informed volume of extraction of 3 million m^3 per year, however this data may vary since effective volume extracted could be higher.

1.5. Limitations

During this investigation, several limitations rose up, these included:

- Existence of illegal gravel mining: local sources have verbally informed that illegal gravel mining takes place in the Maipo river. This means that potential measurements of extracted volume could possibly be higher than oficially reported volumes.
- Budget restriction: Topographic survey cost for the entire study reach is significantly higher than the available budget for the researchers, therefore, only specific zones of interest from the study reach were selected to be surveyed.
- Continuity of historical data: Since historical records of river morphology for different periods of time come from different sources (with different purposes),

the covered area of each record does not necessarily match exactly with the covered area of another record. If this were to happen, it is necessary to preprocess the information before performing the analysis.

(a) (b)

Figure 1.4. Examples of gravel mining in the Maipo river

1.6. Outline of this study

This investigation aims to study the Maipo river in a more scientific way, by using state of the art methodologies and procedures in order to compare the historical evolution of the river with those studied in Europe. The goal is to find similarities or differences between the cases so a future trend can be predicted and measures can be taken towards river management and restoration.

(a)

(b)

Figure 1.5. (a): The foundations of the bridge are exposed due to continuous degradation of the riverbed. (b): The Maipo river is also used as a garbage dumpster by local communities.

To achieve this goal, the first step, pointed out by many authors is to perform a hydromorphological analysis of the river, by consolidating historical information (Comiti et al., 2011; Kondolf, 1994b; Scorpio et al., 2015; Sowik, 2015). In this case, information regarding the river was gathered from the 1950s to year 2015, and then analyzed to find patterns and correlation between morphological changes and socioeconomic development.

To achieve this, aerial photographs, satellite images, and topographic surveys were used in order to locate and measure planform changes and elevation changes on the riverbed and active channel.

For a more detailed analysis and a more accurate measurement, a Difference of DEMs (Digital Elevation Model) was also performed to calculate exact volume change based on the comparison of two sets of surfaces.

With this information, the results are exposed and analyzed trying to find a trend that could help anticipate the river response to anthropic intervention. These same results and trends are compared with a socioeconomic analysis regarding urban population development and construction industry dynamics in the study area.

1.7. Thesis structure

This document is divided into four chapters. In the first chapter, the motivation and main context of the investigation is presented. The second chapter contains the article written based on this research. It consists of an introduction, description of the study area, description of the materials and methods used, then results and discussion are presented. The third chapter shows the conclusions of this investigation, while the fourth chapter exposes some final remarks and outlines the future work ahead.

2. MORPHOLOGICAL EVOLUTION OF THE MAIPO RIVER IN CENTRAL CHILE: INFLUENCE OF IN-STREAM GRAVEL MINING

2.1. 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 they 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 (Comiti et al., 2011; Kondolf, 1994b; Surian & Rinaldi, 2003).

These effects have been widely studied in Europe, specially in Italy (Belletti, Nardi, & Rinaldi, 2015; Comiti et al., 2011; Scorpio & Rosskopf, 2016; Surian & Rinaldi, 2003, 2004; Zanoni, Gurnell, Drake, & Surian, 2008; Ziliani & Surian, 2012), Spain (Batalla, 2003; Martín-Vide, Ferrer-Boix, & Ollero, 2010), France (Arnaud et al., 2015; Gaillot & Piégay, 1999; Kondolf, Piégay, & Landon, 2007; Petit, Poinsart, & Bravard, 1996; Piegay, Cuaz, Javelle, & Mandier, 1997), United States (Kondolf, 1994a, 1994b) and Poland (Rinaldi et al., 2005; Wyzga, B., Zawiejska, J., Radecki-Pawlik, 2014; Zawiejska, Wyga, & Radecki-Pawlik, 2015).

In Italian rivers gravel mining has been identified as the main driver in river adjustements (Scorpio & Rosskopf, 2016; Surian et al., 2009), same case as Spain (Batalla, 2003), however, this has not been the case in France, where rivers have shown that channelization and afforestation have predominance (Kondolf et al., 2007), along with the presence of dams (Warner, 2012).

Although effects on rivers may be different by depending on the degree of human intervention, it is clear that there is a strong temporal relationship (Rivas et al., 2006; Surian & Rinaldi, 2003), with rivers being highly responsive to human impact (Belletti et al., 2015) and even showing inertial effects (Martín-Vide et al., 2010). Some rivers have shown the capability to recover when human activities stopped at the river (Comiti et al., 2011; Scorpio & Rosskopf, 2016).

To study these effects and understand the current and long term conditions, a historical analysis on the river morphology is required (Kondolf, 1994b). Planform analysis has been performed throughout the years by the use of maps and air photographs (Arnaud et al., 2015; Comiti et al., 2011; Downward et al., 1994; Gurnell, Downward, & Jones, 1994; Hughes, McDowell, & Marcus, 2006; Little, Richardson, & Alila, 2013; Zanoni et al., 2008). These remote sensing techniques have proven to be quite accurate measuring landscape properties (Mertes, 2002). Some examples are: adjustment of the active corridor width and land cover changes (Comiti et al., 2011; Zanoni et al., 2008), active channel (Arnaud et al., 2015; Comiti et al., 2011) and vegetation boundaries (Arnaud et al., 2015; Comiti et al., 2011). Cross section topographic sampling and analysis has been used to estimate sediment budget, incision or deposition (Arnaud et al., 2015; Gob, Houbrechts, Hiver, & Petit, 2005). Technological improvements have allowed the use of Digital Elevation Models (DEMs) to directly calculate sediment budgets (James et al., 2012; Lane et al., 2003; Milan, Heritage, Large, & Fuller, 2011; Wheaton, Brasington, Darby, & Sear, 2009). These DEMs are constructed upon digital photogrammetry, laser altimetry and image processing to provide a complement for cross section analysis

Italian rivers have shown a common pattern of evolution of their morphology (Scorpio et al., 2015; Scorpio & Rosskopf, 2016; Surian & Rinaldi, 2003, 2004; Surian et al., 2009) in the last 150-200 years, with incision and narrowing as the main processes at the initial stages from (early nineteenth century, to the 1980s-1990s), being the most intense period between the 1950s to 1990s and then a widening and sedimentation phase afterwards. It has been shown that sediment mining and dam construction had a main role in the incisioning and narrowing phases with an intense effect at the beginning and then becoming slower towards asymptotic state.

The incision process has been observed to be closely tied with gravel mining and vice-versa (Kondolf, 1997), with average values of river bed incision in the order of 4 to 10 m (Surian & Rinaldi, 2003; Wyzga, 2007) and in some cases, incision has been persistent even though mining operations have stopped (Comiti et al., 2011; Martín-Vide et al., 2010; Surian et al., 2009), evidencing the "inertia" effect. Narrowing has been observed in the active channel for braided rivers to an order of 50% (Surian & Rinaldi, 2003), changing the pattern to a wandering one, however, it has been observed that once the gravel mining stops, the active channel starts to widen back again Comiti et al. (2011). Although most cases have experienced incision alongside narrowing, there has been exceptions where incision and widening have taken place combined (Bollati, Pellegrini, Rinaldi, Duci, & Pelfini, 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).

In addition to the accelerated urban expansion and changes in land-use and cover, many rivers in developing countries are also affected by in-stream gravel mining, which is one of the most important disturbances that has severe consequences on rivers, producing rapid incision and narrowing of the channels (Wishart, Warburton, & Bracken, 2008). In several countries in South America, most of the urban growth has occurred in mountainous regions or the piedmont near the Andes, where the rivers have been additionally impacted by 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 hydromophological approach on river management (Andreoli et al., 2012) and methodologies for optimization of exploitation of resources have been proposed (Godoy, Gatica, Niño, & Mcphee, 2010), however there has been little study and most scientific evidence is available locally and any kind of analysis performed in other latitudes must be adapted to the local context.

Designing river management measures and restoration strategies in these regions is a very complex task, due to the lack of regulation and control of anthropic activities that induce morphological changes. The analysis is further complicated by the lack of data, since in most of the river basins in the Andes there are short records of hydrometeorological data, and incomplete information of the geomorphology and soil properties of the watersheds.

The Maipo river, located in central Chile, is a suitable candidate to study: a gravel-bed Andean river with several interventions. The river originates in the Andes mountain range, and drains to the Pacific Ocean, flowing through the southern part of the city of Santiago serving a total basin population of about 5.3 million (35% of the total chilean population). The Maipo river has been selected due to its proximity to the urban area, which has prompted an intensive use of water in the last century for agriculture and water supply, and the hydropower installation capacity of more than 300 MW.

To understand the geomorphologic evolution of this Andean river and assess the impact of human intervention, this investigation performs an analysis of the area where most of the sediment extraction activities operate. The objectives of this investigation are to: (1) quantify planform and elevation changes of the river channel; (2) to relate the channel evolution to the urban growth within the watershed; and (3) to establish guidelines for restoration, based on the findings of this study.

This work aims to contribute to the development of sediment budget analysis on South American rivers. The results exposed in this paper could help to understand the magnitude of persistent human impact on rivers where natural or artificial restoration is difficult to achieve due to the many economic interests laid on the river itself. Specifically, these results can be used for the development of a river management plan which would involve communities, stakeholders and public policies to work on a sustainable exploitation of the river resources. Future work could use this investigation as a starting point for a smaller scale study on sediment budget, river hydromorphology and management.

Channel adjustments on the Maipo river in the last 60 years are studied, where gravel mining activity is tracked by combining all the available historical maps, aerial photographs, and topographic data. Morphological evolution of planform parameters such as channel bankfull width, braiding index, and sinuosity are measured from the qualitative and quantitative analysis of the data, and by collecting new relevant information in the field. To measure human activity impact, land cover changes such as sediment bars and their location, along with gravel mining operations sites that are identified and studied under a planform perspective measuring the surface two-dimensional (2D) area. River surface evolution is analyzed using digital elevation model difference (DoD) to assess how incising and/or narrowing have developed in the study area due to gravel mining. For this purpose, an estimation of the extracted volume is performed for the study period, reconstructing the changes of the channel and linking them to urban growth and economic activities, associating also possible trends and links with the population development and historical economic statistics.

This paper is organized as follows. In section 2.2 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 2.3. In section 2.4, evolution of the Maipo river through the calculation of morphological parameters is reported. In section 2.5 the relation among these parameters and the consequences of in-stream gravel mining is discussed. Finally, the conclusions summarize the findings of this investigation and outline topics for future research.

2.2. 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. 2.1). The river headwaters lie at the foothills of the Maipo volcano (3,135 m asl), in the Andes mountain range. Most drinking water and irrigation supply in the region is provided by the Maipo river, approximately 70% and 90%, respectively.

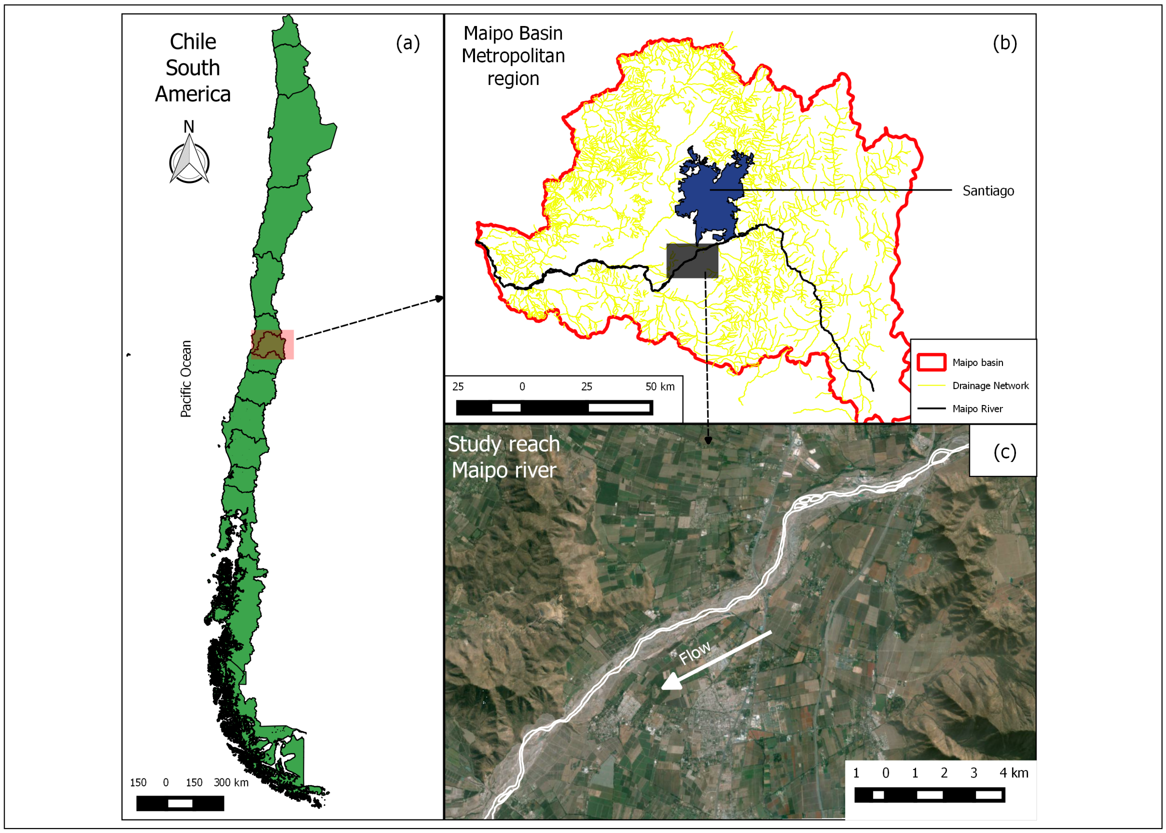


Figure 2.1. Location of analyzed reach in central Chile (1a). The Maipo river flows from east to west and is located directly south of Santiago city (1b) in the Maipo basin. The river at the study reach flows NE-SW and it is approximately 22 km long (1c).

The climate is mediterranean with an extended dry season, although recent studies show a warming trend in the central valleys of Chile (Cortés, Vargas, & McPhee, 2011). The dry season starts in April and ends in October, which corresponds to autumn and winter seasons. During spring and summer seasons, the snow melting in the Andes raises the discharge in the Maipo and its tributaries, making the river specially sensitive and dependent on snowmelt for irrigation purposes (Cortés et al., 2011). Historical month average flow is 104 m^3/s, while snowmelt season (october to march) average discharge is

151 m^3/s and the winter season (april to september) has an average month discharge of 57 m^3/s, showing an approximate of 50% variability (Fig. 2.2).

The Maipo river is a key element for the basin and the city of Santiago, since it has been directly involved in major events that have caused significant effects on the cities and local towns, mainly alluviums and water supply interruption through the years (Sernageomin, 2016).

In the context of a changing climate and rapid urban growth, the Maipo river serves a great economic demand (Rosegrant et al., 2000), in which two additional factors have played a significant role on the morphological changes: (1) The particular method of using market dynamics in water management in Chile; and (2) The increasing development of urban population by 268% in the Metropolitan Region of Santiago since 1960 (Hearne, 1981). Water rights in Chile are allocated privately and proportional to "stocks", which can be traded, and have been granted in the Maipo watershed for agriculture (mostly owned by 7 associations), and hydropower generation that diverts the water, which is returned to the river channel downstream. The city has now an approximate population of 6 million, which has increased the pressure for water supply. This very water supply system is subject to high risk of failure due to increasing turbidity caused by warm storm in the Andes region. Warm storms raise the freezing level in the ravines and foothils of the Andes mountain range increasing the water volume available causing flooding, landslides and debris flows if precipitation is intense or prolonged (Garreaud, 2013). These hazards have shown to cause a similar amount of damage and fatalities than earthquakes (Sepulveda, Rebolledo, & Vargas, 2006).

This investigation focuses on the specific reach of the Maipo river (Fig. 2.3a), which has been selected as it expressed the largest impact of in-stream gravel mining. In this part of the channel, the Maipo river flows in a west-southwest direction, such that the river banks are defined as the north (right) bank and the south (left) bank. The study reach is approximately 22.1 km long, with an average slope of 0.009 and an approximate stream power value of 5 kW/m and 13 kW/m in the low and high season respectively. The

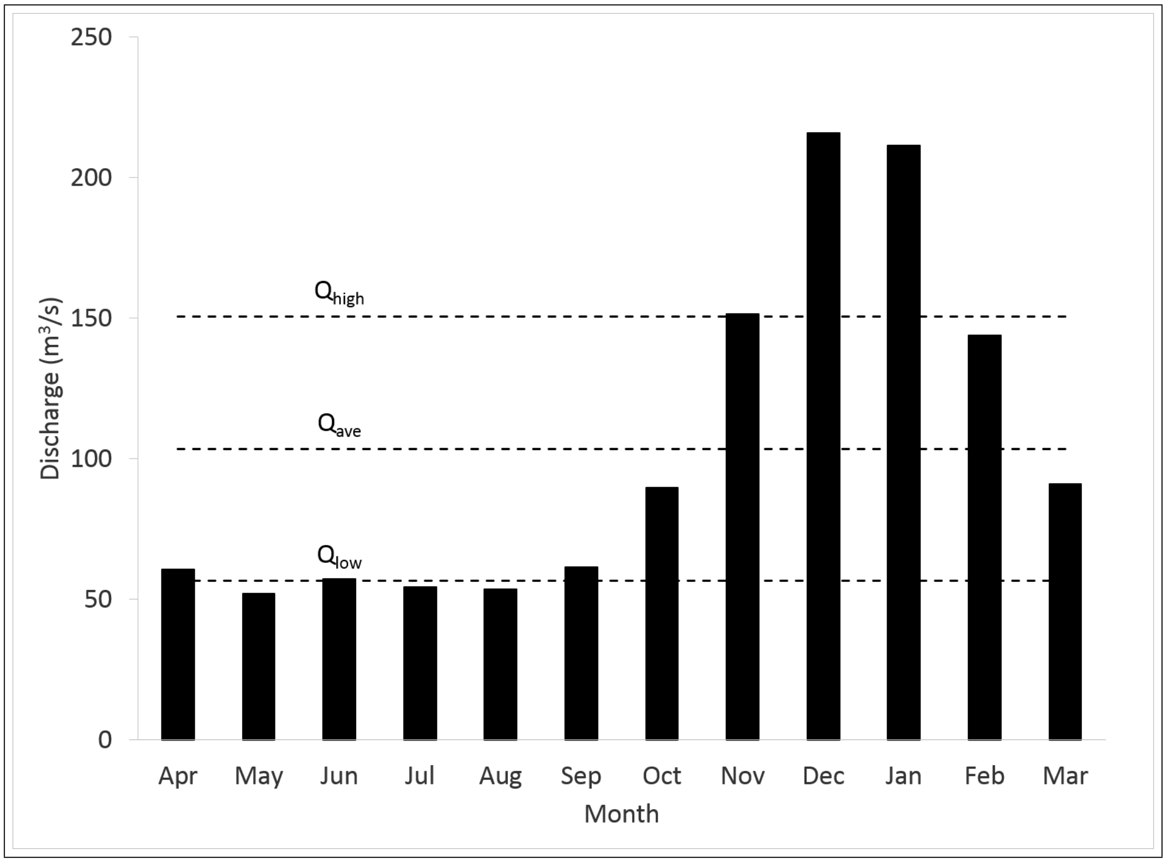


Figure 2.2. Month average discharge of the Maipo river measured at the sector known as *La Obra* (Fig. 2.3b) (1965-2010). Low (Q_{low}) and high (Q_{high}) season average discharges are plotted and show a 50% variability with respect to the total month average Q_{ave}.

infiltration losses in the study reach have been estimated between 0.1 and 6.7 m^3/s (DGA Direccion General de Aguas, 2003).

The reach is characterized by the presence of important infrastructure that has been built particularly over the last 60 years. At the upstream section of the reach, there are three water intakes (Fig. 2.3b). The largest, which is indicated as (b.1) comprises a sluice gate whose default operation status is to be closed towards the main channel, working as a diversion dam, giving water to the irrigation channels present (b.2) and (b.3).

3 km downstream there is a gate (c.1) that diverts flow towards another irrigation channel. In this section there are two bridges across the Maipo river (Fig. 2.3c), being the Route 79 bridge (c.2) the most important.

Approximately 8 km downstream from Route 79 bridge, there are four more bridges crossing the river (Fig. 2.3d). These bridges are part of the Route 5 river crossings, the most important road in Chile, which connects the country longitudinally from the far north to south.

At 8 km downstream of Route 5 bridges, there is a small canyon where the river cross-section is narrowed from 600 meters wide to 150 meters, this feature is located between two hills, *Puntilla Lonquén* and *Cerillos la Finca*.

As a result of this layout, all available water is taken from the river to the irrigation channels as much as the water stocks allow it for the different owners. If there is any surplus water available, it is given back to the river via intakes (b.1) and (c.1), known as *Clarillo* and *Unidos de Buin* intakes respectively, however it is challenging to measure how much water is available in the river itself since no flow gauges are installed after intake (c.1). Additionally, local sources state that surplus water is actually rare and there is a lack of management and surveillance when floods occur since all associations focus on their own channels and close their gates. Due to the almost complete water allocation, the study reach is virtually dry for most of the time, leaving little to none sediment recharge possibilities. This is due to the fact that several gravel mining sites and storing facilities are present along the study reach. The authority to issue permits for gravel mining falls to local city halls as stated by chilean law.

2.3. Materials and methods

In this investigation, planform and elevation morphological changes are assesed using available aerial photos and topographic surveys for the last 60 years. Planform changes are determined using aerial photographs, satellite images, and historical maps, while elevation

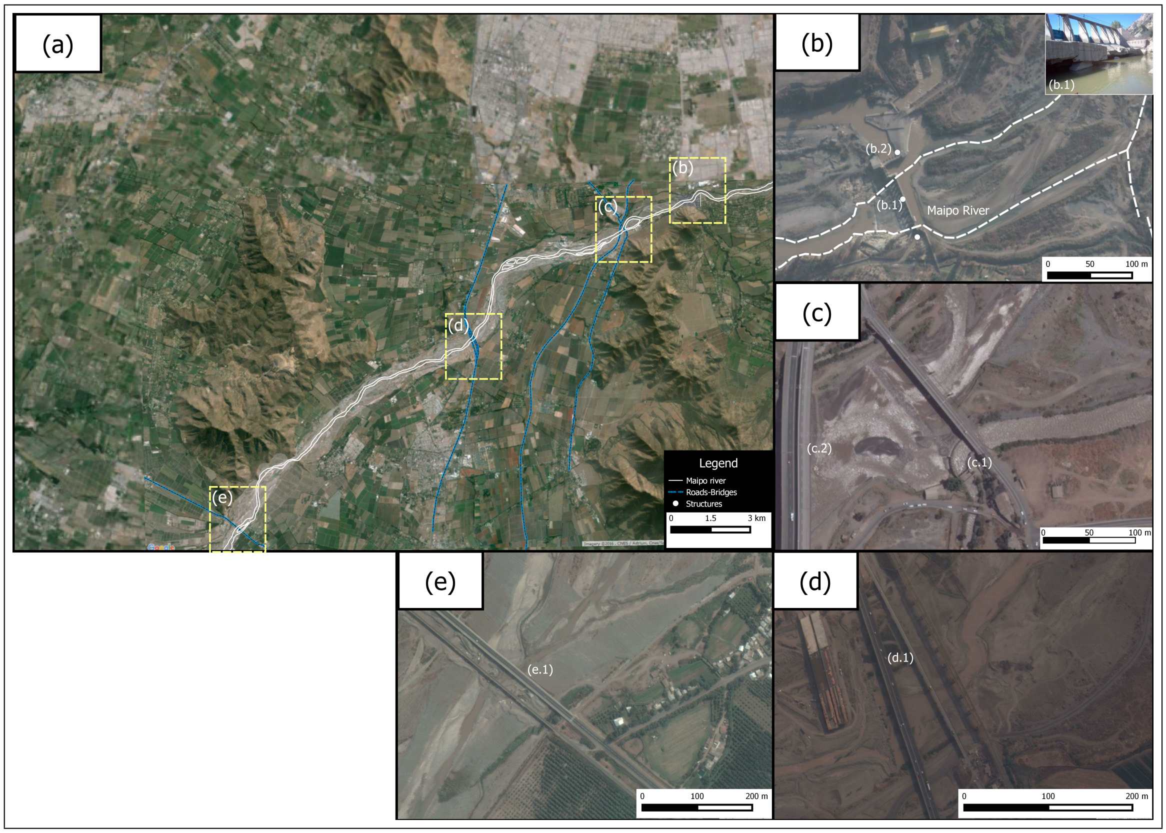


Figure 2.3. (a) Maipo river study reach. The four crossing zones are labeled b to e. (b) Upstream boundary gate b.1 is closed so intakes b.2 and b.3 can take water from the river and supply the irrigation channels. (c) Gate c.1 returns water to the Maipo river next to the Route 79 bridge (c.2) and also supplies another irrigation channel. (d) The Route 5 bridge array, connecting the southern cities with Santiago. There are currently 3 operational bridges while a fourth one is under construction due to highway demand increase. (e) Downstream boundary e.1 for the study reach.

changes are measured using topographic data and surface contours obtained from different methodologies over the years.

According to the spatial distribution of the anthropic intervention in the river, the study reach was divided into three sub-reaches. The first sub-reach extends from the upstream boundary (Fig. 2.3b)), to the Route 79 bridge (Fig. 2.3c). The second sub-reach extends from the Route 79 bridge to the Route 5 bridge (Fig. 2.3d). Finally the third sub-reach extends from the Route 5 bridge to the La Puntilla bridge (Fig. 2.3e), the downstream boundary of the study reach.

Fig. 2.4 shows the study reach and longitudinal discretization with the cross-sections marked on the channel. The original data of the reach and river banks was obtained from aerial photographs taken in 1954 that were digitized, creating three alignments following the centerline between the river banks. Each alignment corresponds to a sub-reach, where sample lines were plotted every 100 m for planform analysis, and every 200 m to carry out the study of changes on the topography. A special refinement, however, was performed in the vicinity of Route 79 and Route 5 bridges, where highly detailed data was measured and reported every 20 m.

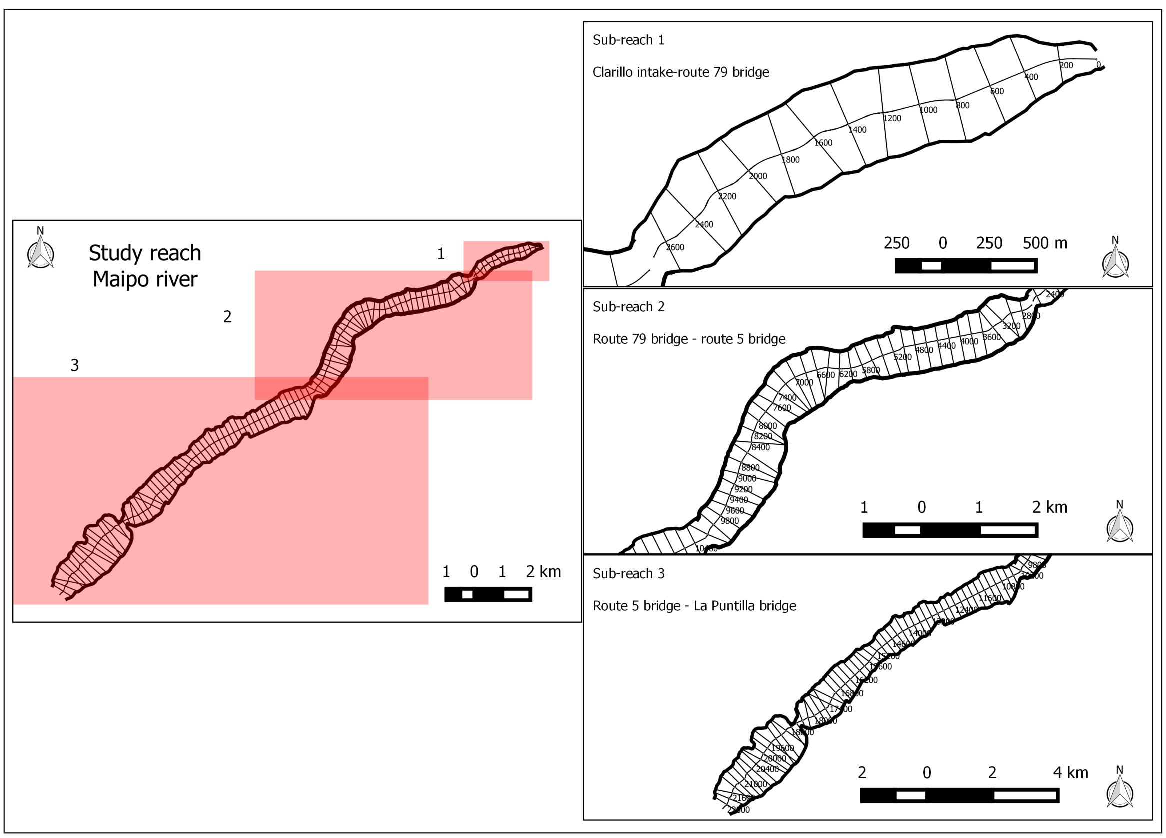


Figure 2.4. Study reach discretization. The study reach is divided into three (1) upstream boundary-Route 79 bridge. (2) Route 79 bridge-Route 5 bridges. (3) Route 5 bridges-downstream boundary.

2.3.1. Land cover and morphological 2D changes using maps, air photographs and satellite images

The main sources of information surveyed were aerial photographs from years 1954, 1992, 1994, 1997 and 2008 provided by the Aerial Photogrammetry Service of the Chilean Air Force SAF, and the Geographical Institute of the Chilean Army IGM, along with Google Earth imagery from year 2015. A historical map from 1980 was also used to complement the analysis.

SAF aerial photographs were scanned using 600 DPI resolution and georeferenced using approximately 15 ground control points for each photo such as street intersections, building corners, and bridge columns (Gurnell et al., 1994), and registered to a common base using QGIS 2.8 software. IGM photographs from 1954, on the other hand, were already provided on digital format. A total of 12 control points were used for each photograph, and Google Earth imagery was also registered to the same mapping base using from 10 to 20 points using Helmert transformation with minimum error. Several screenshots were taken to achieve the best resolution possible for feature identification.

All photographs were taken during winter season, where the flow is at its minimum level, allowing the assessment and identification of most river features.

The map from 1980 was issued under a PSAD56 coordinate system, which was reprojected to the WGS84 19S system for digitizing, using map grid intersection points as control points under the QGIS software environment. This re-projection technique has been used to achieve greater accuracy as described by Gurnell et al. (1994). Thin plate spline (second order radial basis function) and polynomial interpolation functions were used for georeferencing.

Finally, aerial low altitude ortho-rectified photographs were taken using an Unmanned Aerial Vehicle (UAV), to improve the resolution near the Route 5 and Route 79 bridges, covering over 90 hectares of each zone. These photographs were also georeferenced to the

QGIS database as the UAV carried a GPS receiver. The UAV flights provided high resolution images, with a ground sample distance of 2.83 cm. The UAV flight was performed in May, 2015, during autumn season, under low flow conditions.

Table 2.1 shows a summary of resolutions and image scales is listed for all sources. All of the sources mentioned above allowed to identify several features such as river banks, irrigation channel intakes, islands, active channels, and bridges.

Table 2.1. List of data sources used on this study

Image Series	Type of image	Source	Year	Scale/Altitude/Resolution	Grayscale/Color
1	Air photo	IGM	1954	1:50000	Grayscale
2	Historic map	IGM	1980	1:20000	Black & White
3	Air photo	SAF	1992	1:20000	Grayscale
4	Air photo	SAF	1994	1:20000	Grayscale
5	Air photo	SAF	1997	1:70000	Grayscale
6	Air photo	SAF	2008	1:20000	Color
7	Satellite Image	Google Earth	2015	1:2500	Color
8	UAV Air photo	This study	2015	85.5 m., 2.83 GSD	Color

2.3.1.1. Morphological analysis

For years 1954, 1980, 1992, 2008 and 2015, the sinuosity of the channel was calculated, using the parameter of Friend and Sinha (1993), which corresponds to a modification of the classical sinuosity defined by Leopold and Wolman (1957), to fit multi-channel situations. This parameter is defined as follows,

$$P = \frac{L_{cmax}}{L_R} \tag{2.1}$$

where P is the sinuosity, and L_{cmax} and L_R correspond to the mid-channel length of the widest channel, and the linear distance measured with a straight line between the end points of the reach, respectively. The braiding index (BI), on the other hand, is taken as the average number of parallel channels every 100 m. Control points are plotted below every 100 m, through the centerline of the widest channel when parallel channels are present.

The 1954 set of photographs allowed the identification of active channel, islands and river banks. This set will be used as a base for historical comparison of the active channel. The active channel was marked in the QGIS database as a polyline, while the islands and bars were marked using polygons. Gravel mining sites could not be identified due to the large scale of the photograph set (1:50000), but the operations were minimal at the time.

The 1980 historical map allowed us to identify the river banks, along with irrigation channel intakes and outlets. Islands and presence of sediment deposits was also identified, with an approximate area covered by these of 120.1 hectares.

From the 1992 and 1994 photographs, river banks, active channels, islands, and gravel mining sites were identified. All these features are marked with polygons and polylines in the QGIS database. The 1997 photo set was disregarded because its scale (1:70000), as it was not possible to identify any features except for the river banks. The 2008 full color photograph set allowed to identify the river banks, active channels, islands, and gravel mining activities. The same features were also available for the 2015 set.

Human intervention on the river such as gravel extraction and storage, sediment processing plants, and construction sites, are features than can be clearly identified because of their precise shapes (i.e., excavators, or backhoes machinery). Fig. 2.5 shows examples of anthropic activities introduced into the river channel.

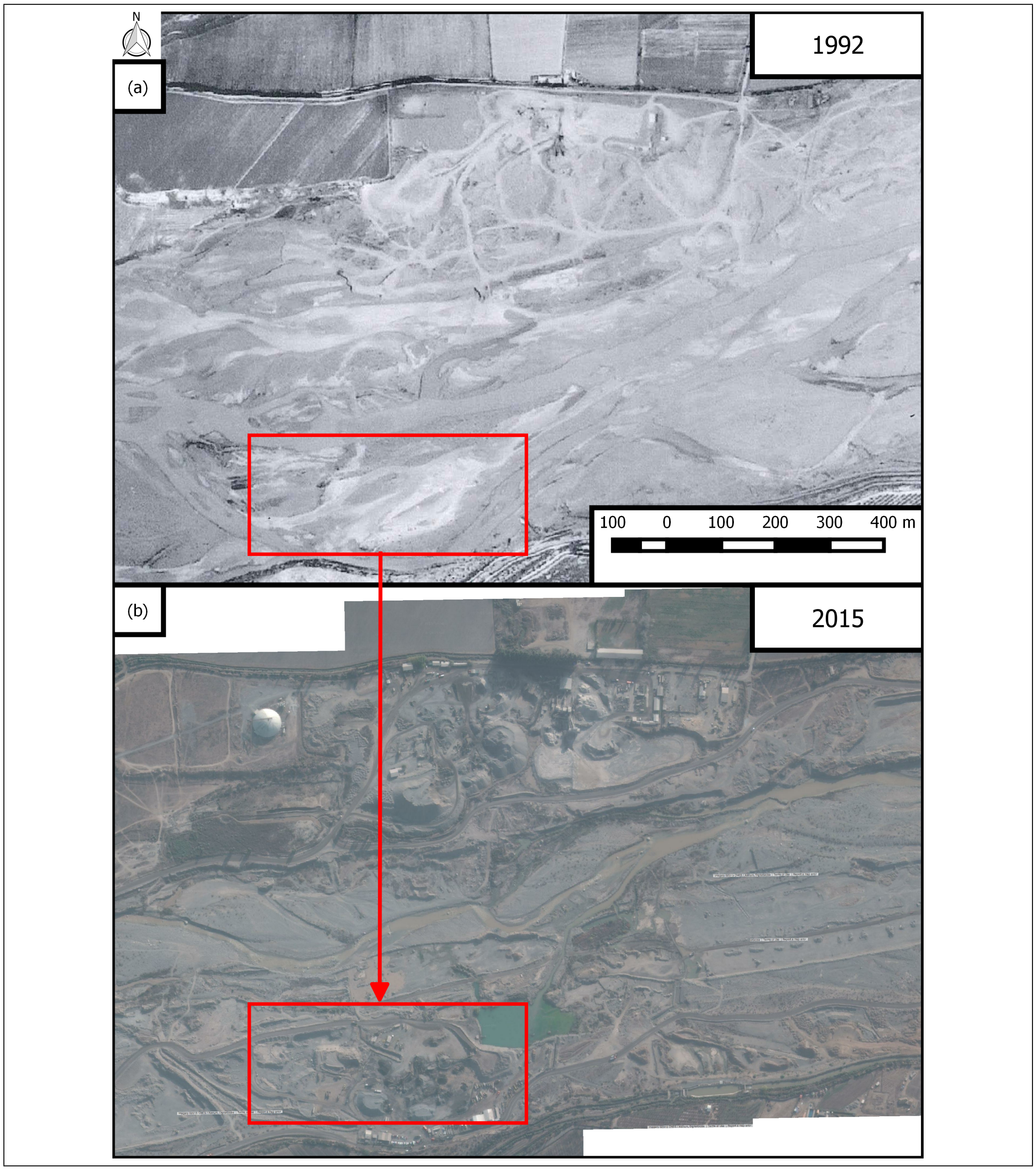


Figure 2.5. Introduction of human activity. Precise straight shapes can be identified from above. In (a), the river flows naturally over the south bank (highlighted), however, 23 years later (b), human intervention takes place and the main channel switches to the north bank.

2.3.2. River longitudinal profiles and cross-section analysis using historical topography and DEMs

Topographical data for years 1980, 2007, 2009 and 2011 was acquired from data collected for irrigation management purposes. Current data for 2015 was acquired using GlobalMapper software v15.2.3 Geographics (2009), and complemented with a high resolution digital point cloud that was taken on site with a UAV for this study, comprising an area of 180 hectares surveyed. Table 2.2 shows the contour resolution for the data from each source.

A local coordinate system was created for the historical comparison. The alignment was divided into three segments, one for each sub-reach. The total length of the alignment is 22 km, and control sections were taken every 200 m for bankfull width and thalweg measurements. As topographic data does not correspond exactly with the size of the reach, the minimum extent was taken into account as the baseline for historical comparison, which corresponds to the 2011 topography. Table 2.2 shows all the topographic data sources and their extent in terms of the alignment station length.

Table 2.2. Resolution of elevation data

Year	Source	Resolution	Max. extent (station)
1980	Historic map	2.5 m contours	22,000 m
2007	Topography	0.5 m contours	22,000 m
2009	Topography	2.0 m contours	18,200 m
2011	Topography	10.0 m contours	18,000 m

The 1980 historic map included 2.5 m interval contours which allowed us to create the 3D surface of the terrain, and the 2007 topography data contained 0.5 m interval contours. Surface data from 1980 to 2011, and 2015 GlobalMapper data were transformed to DEMs and used to calculate the difference of DEMs to estimate the volumetric change in the river bed.

2.4. Results

2.4.1. Morphology features: Planform changes

Fig. 2.6 shows changes in the active channel evolution from 1954 to 2015 for all sub-reaches in each of the subplots corresponding to the columns. The active channel in sub-reach 1 highly depends on the operation of the water intakes and irrigation channels present in the area, and also on the three outfalls or return pipes located on the north bank, which serve as drainage structures of the surrounding area (i.e: irrigation channels) if there is surplus water. The surplus water is delivered to the river and conveyed through the north portion of the floodplain. These water threads can be seen from 1954 to 2008. The active channel has suffered a migration process to the south bank. In 1954, sub-reach 1 shows a clear braided morphology until 2008. In 2015 the north portion of the main channel remains dry as the drainage structures did not return water to the river. Between years 1992 and 2008, an artificial channel was excavated to divert water from Clarillo intake, denoted as c.2 in Fig. 2.3c, directly to the south bank.

In sub-reach 2 the main threads maintain their relative position throughout the years, close to the north bank of the river. In this case, however, the river suffers a transition from braided to single thread, similar to the case of sub-reach 1, with the exception that no artificial channels are excavated in this section, and no water intake structures are present. From 1954 to 1992 some threads reach the south bank, but from 2008 onward the threads disappear and only the main channel remains to exhibit some isolated braids.

Sub-reach 3 exhibits a very intense braided pattern in 1954, then a slight decrease on the braiding pattern takes place in 1980 and remains almost constant in 1992. A new and stronger decrease takes place for years 2008 and 2015. The narrowing occurs along the entire reach with the central portion being the most affected.

To characterize the curvatures of the channels, the sinuosity was calculated for the whole study reach, and it was also segmented for each of the sub-reaches separately. Fig.

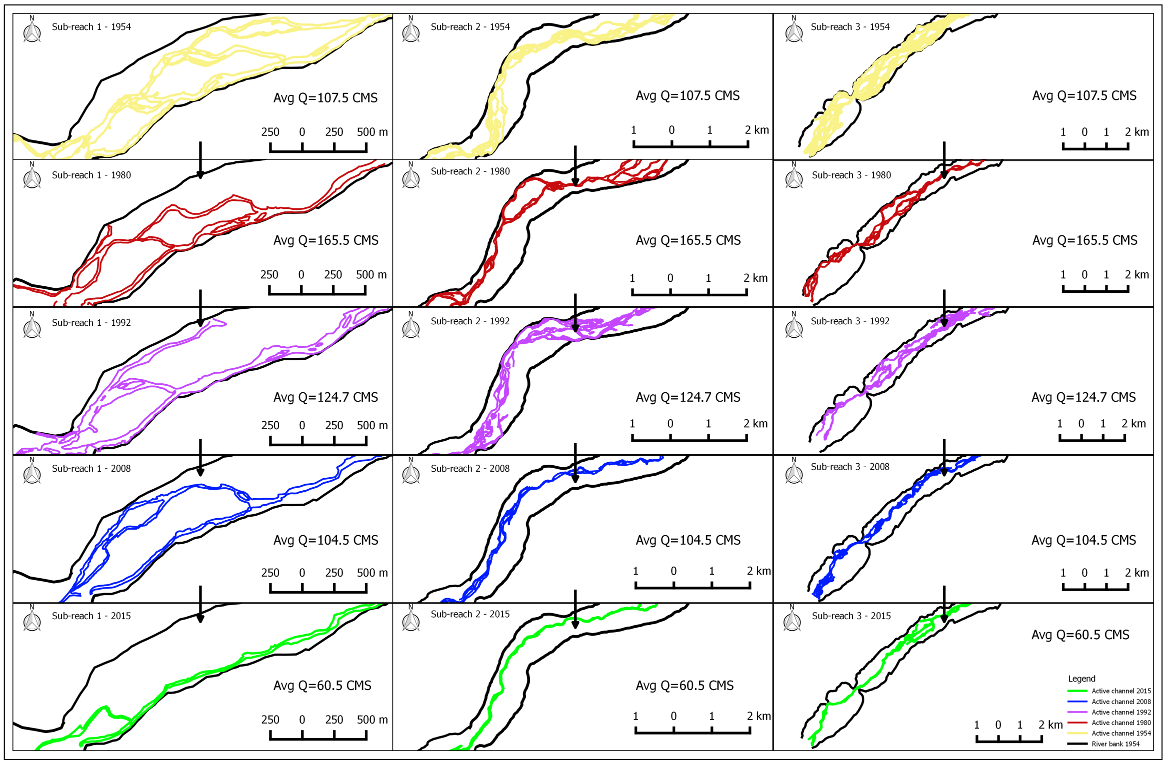


Figure 2.6. Identification of the active channel of the Maipo River from 1954 to 2015. Columns 1 to 3 correspond to sub-reaches 1 to 3 respectively and time evolution is in the vertical direction. Year average discharge is included for each period.

2.7 plots the historical evolution of the river sinuosity, showing an alternating behavior in sub-reaches 1 and 3. Sub-reach 2 shows a negative trend around value 1.2. The absolute maximum value of sinuosity is 1.23 in 1954 and the minimum absolute value is 1.05 for the same year. Except for year 2015, the maximum overall sinuosity is observed in sub-reach 2.

River braiding was also measured for the entire reach of the Maipo River, and for each sub-reach in which the river reach was divided. The analysis shows that all sub-reaches exhibit a negative trend (Fig. 2.7).

The highest BI was given at 1954, with an average of 3.83 for the entire study reach. The BI drops to 2.45 on 1980, then it has a slight decay to 2.28 in 1992. For 2008 there is another significant decrease of the BI to 1.71, and finally in the year 2015 the BI decreases to 1.27. The magnitude of the BI for each sub-reach of the area of study, also shows a decreasing trend as the BI in sub-reach 1 drops from 3.22 to 1 (single channel) from 1954 to 2015, subreach 2 drops from 3.24 to 1.11, and sub-reach 3 drops from 5.02 to 1.69. This analysis also shows that sub-reach 3 appears as the more braided of the three sections, except for 1992 where sub-reach 2 has a slightly superior margin of 3%.

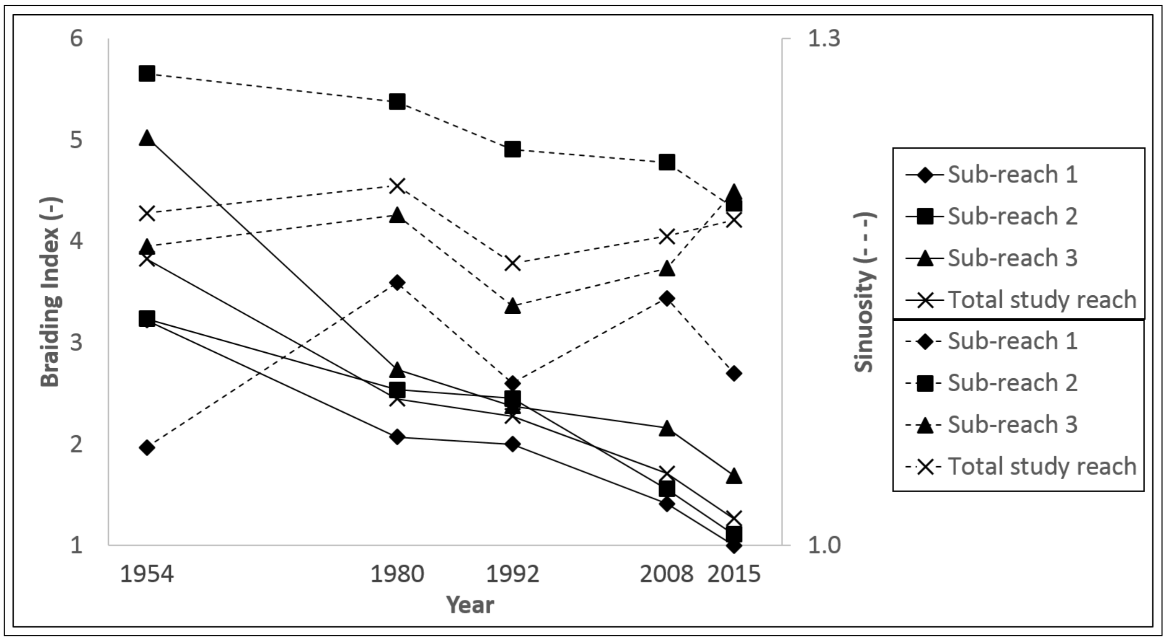


Figure 2.7. Changes of river braiding index (left-continuous line) and river sinuosity (right-dashed line) from 1954 to 2015.

Three main land cover groups were identified to quantify the net change of the river bed extension in this investigation: (1) vegetation, (2) sediment bars and islands and (3) intervened sites (mostly excavation). Vegetation is clearly distinguishable specially when analyzing colored photographs. Bars are mostly given as point bars due to braiding and meanders. Islands can be seen mostly in low flow zones. Finally mining sites can be clearly identified because of the sharp edges performed by machinery as described in section 2.3.1.1.

From the available data, the land-cover evolution of the channel from 1992 to 2015 was obtained. The quality and resolution of the images from 1954 and 1980 are not suitable to extract the area occupation in the reach with the same level of detail. Figs. 2.8, 2.9, and 2.10, show the land cover evolution from 1992 to 2015, depicting an increasing intervention that has transformed the land use on the floodplain during more than 20 years, for each of the subdivisions of the reach.

Figs. 2.11a to 2.11c, show the amount of surface area evolution for the sub-reaches, while Fig. 2.11d shows the aggregate amount of the surface area over the entire study reach. Sub-reach 1 (Fig. 2.8) exhibits an increase from 2.41 to 12.61 hectares on gravel mining area, identified as the intervened area of the channel, which corresponds to a rise of 423% during the observation period. Most of the in-stream gravel mining activities are small operations with no processing nor stocking plants nearby. Vegetation cover remains almost constant between 4.5 and 5.0 hectares and sediment bar land cover drops from 47.74 to 22.19 hectares (Fig. 2.11a).

In sub-reach 2, (Fig. 2.9), there was a significant increase on the gravel mining activities from 29.16 hectares in 1992, to 211.75 hectares in 2015. Processing and storage plants are present on the north and south banks of the river, and large gravel extraction sites can be clearly identified. From 1992 to 2015 the increase on gravel mining surface area influence is equal to an increase of 626%, being the sub-reach with the higher percentage increase for this subject. Vegetation cover remains relatively constant, while river bars surface coverage oscillates averaging a flat trend, as depicted in Fig. 2.11(b).

Sub-reach 3 also experiences a significant increase on gravel mining surface area in the last decade (Fig. 2.10). After staying almost constant from 1992 to 2008, the last period shows an approximate of 261% increase (Fig. 2.11c). While vegetation cover remains almost constant and exhibit a relative 100% increase on the last period, the sediment bar area cover rises between years 1992-2008, but then drops significantly between 2008-2015. It is also possible to realize that the gravel mining activities have been increasing in the downstream direction. Therefore, the analysis of the total land cover evolution (Fig. 2.11d) shows that gravel mining activities have increased dramatically from 86.62 to 368.13 hectares for the entire study reach, comprising a total increase of 325%. The surface area for bars has decreased from 115.68 to 70.90 hectares, which corresponds to a 38% decrease, and vegetation land cover has increased from 17.92 to 33.07 hectares, equal to a 85% increase. Table 2.3 summarizes the results of this analysis.

Table 2.3. Summary of study reach land cover evolution. Note: Percentages are not summable since some of the areas overlap.

Year	Area (% of study reach) Bars	Area (% of study reach) Vegetation	Area (% of study reach) Gravel mining
1992	115.68 ha (6.2%)	17.92 ha (1.0%)	86.62 ha (4.6%)
2008	119.07 ha (6.3%)	20.32 ha (1.1%)	183.73 ha (9.8%)
2015	70.90 ha (3.8%)	33.07 ha (1.8%)	368.13 ha (19.6%)

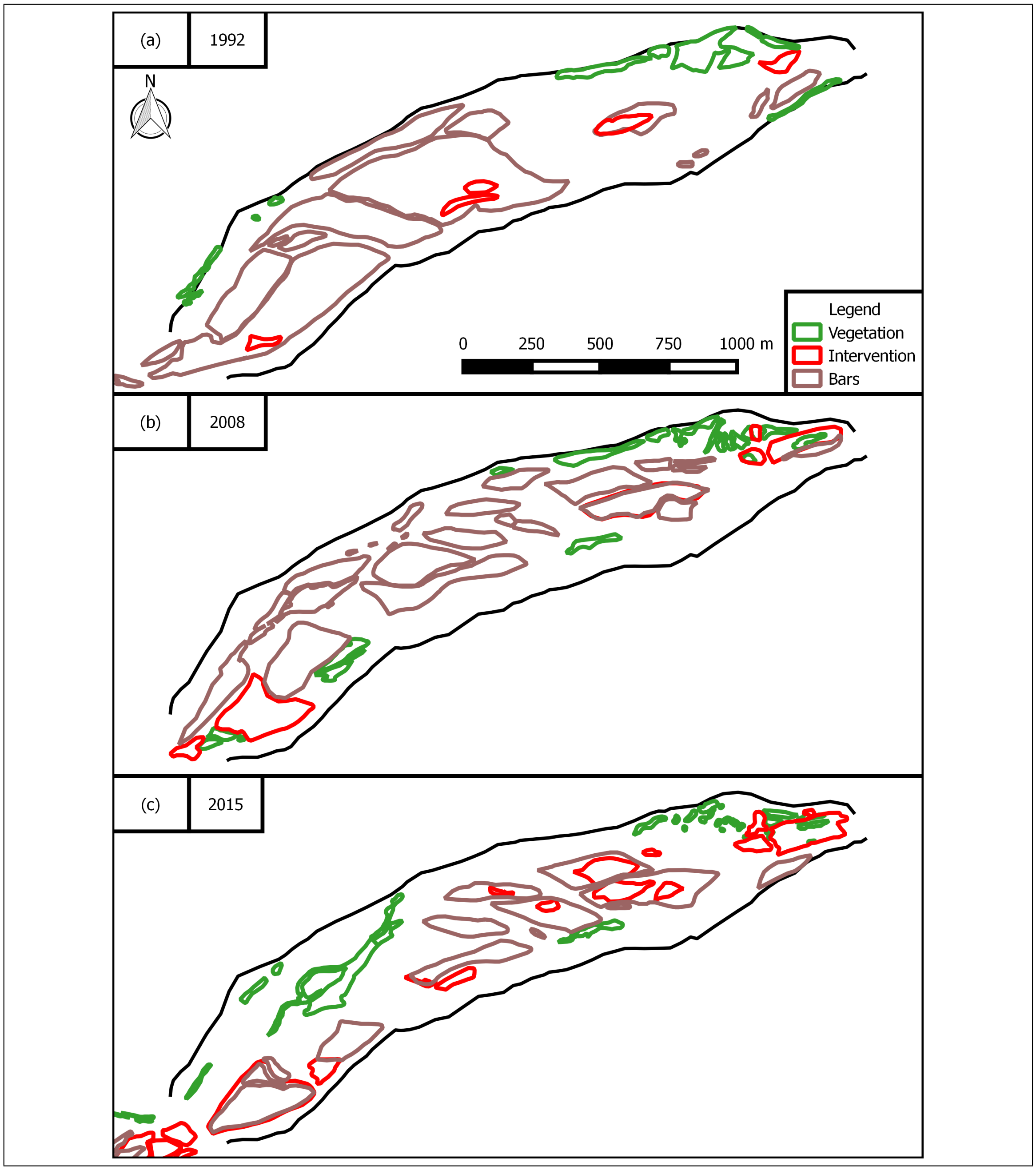


Figure 2.8. Land cover evolution for subreach 1

2.4.2. Morphology features: Elevation changes

The data of bed elevation is used to compute the bankfull width and the thalweg elevation of the river channel, with the purpose of establishing the effects of the in-stream

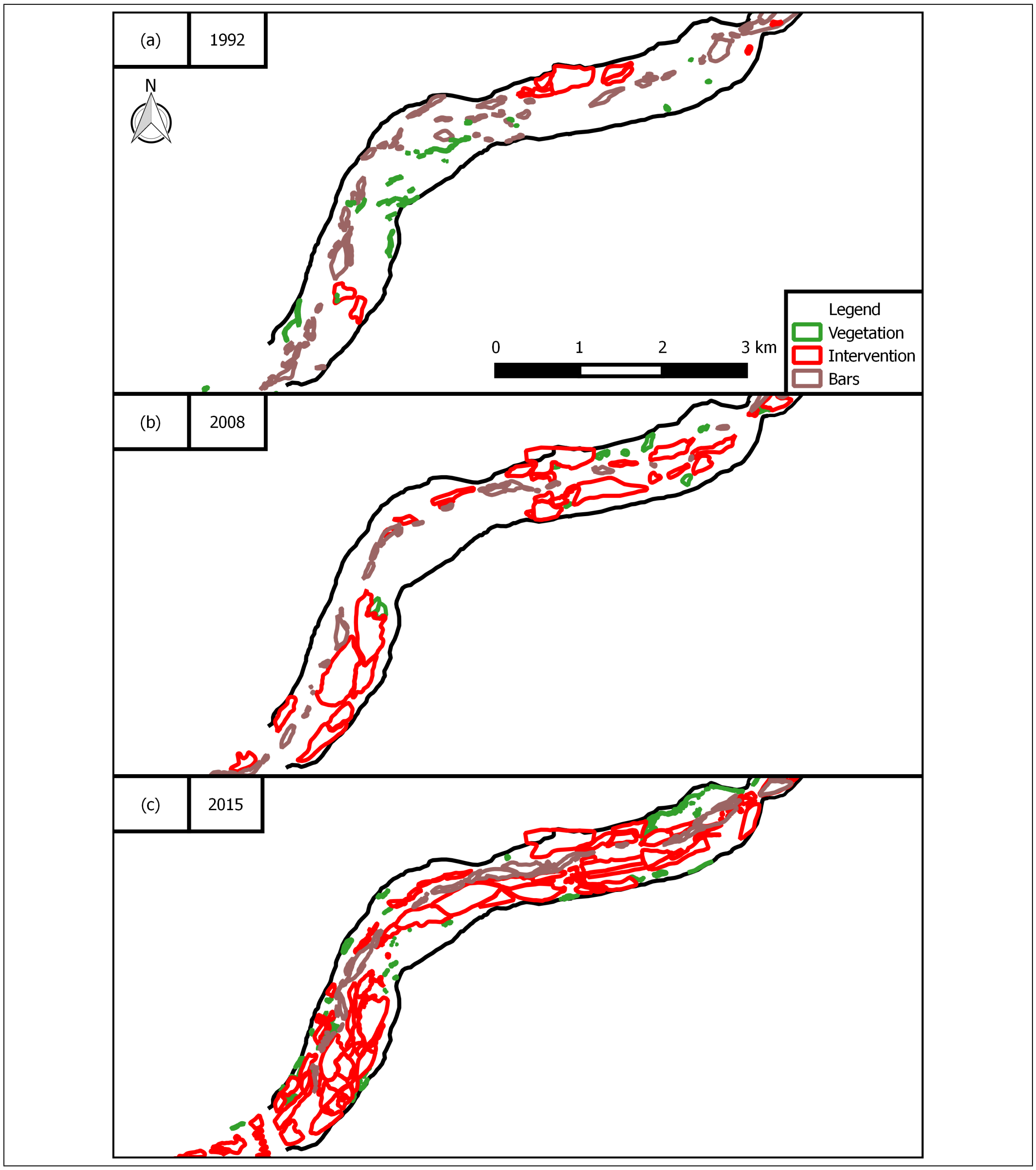


Figure 2.9. Land cover evolution for subreach 2

gravel mining in the Maipo River. The channel bankfull width was measured between 1980 to 2011 using topographic data, for the entire reach and each sub-reach separately (Fig. 2.12). Sub-reach 1 shows a decrease in the bankfull width for almost every station where the cross-sections of the channel were measured. The lowest values can be observed

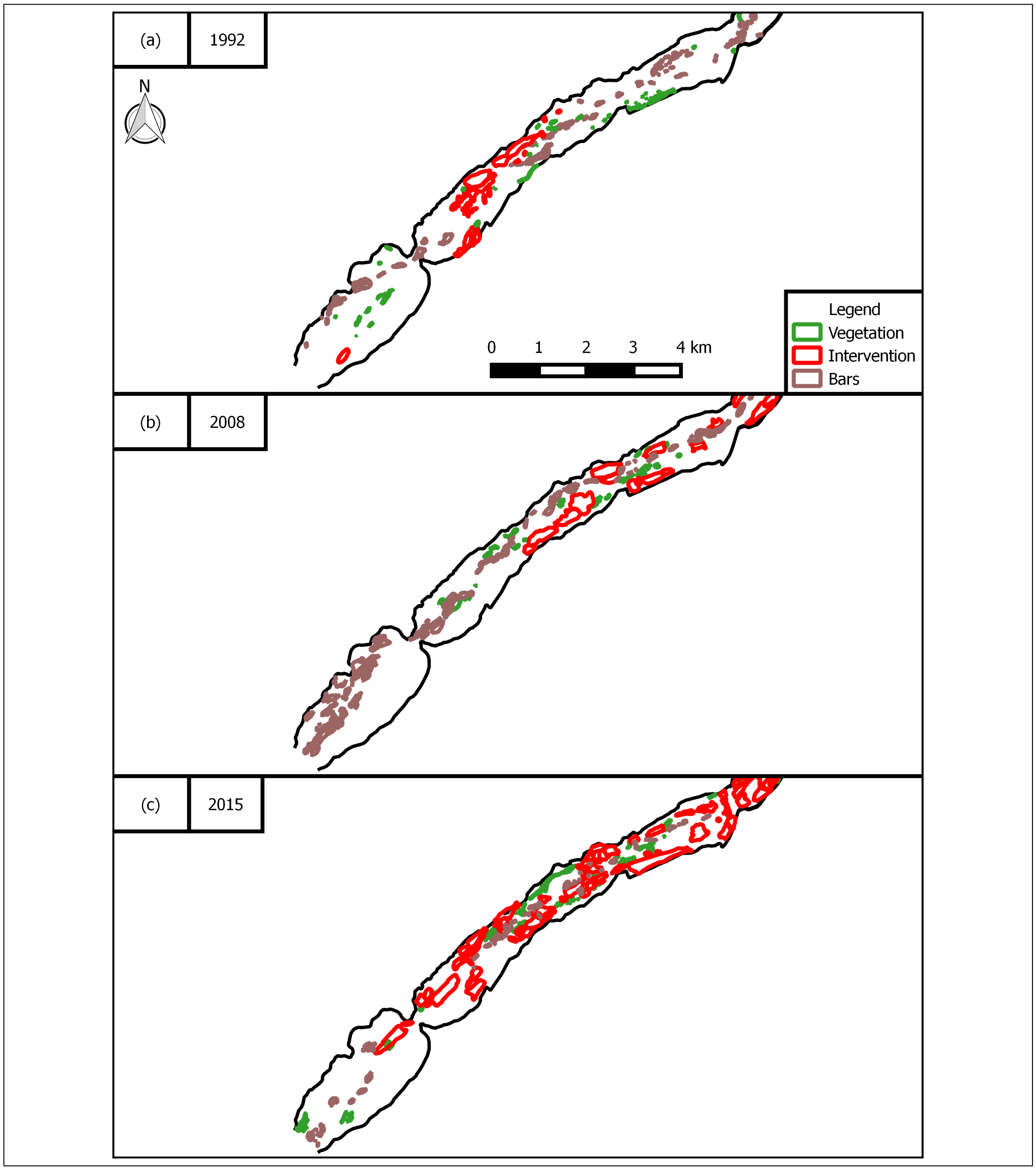


Figure 2.10. Land cover evolution for subreach 3

in 2007, and also a noticeable difference between 1980 and the next three years, specially in the last kilometer, as seen for stations 1,700 to 2,800 m (Fig. 2.12a) which coincide with the construction of the Route 79 access (Fig. 2.13).

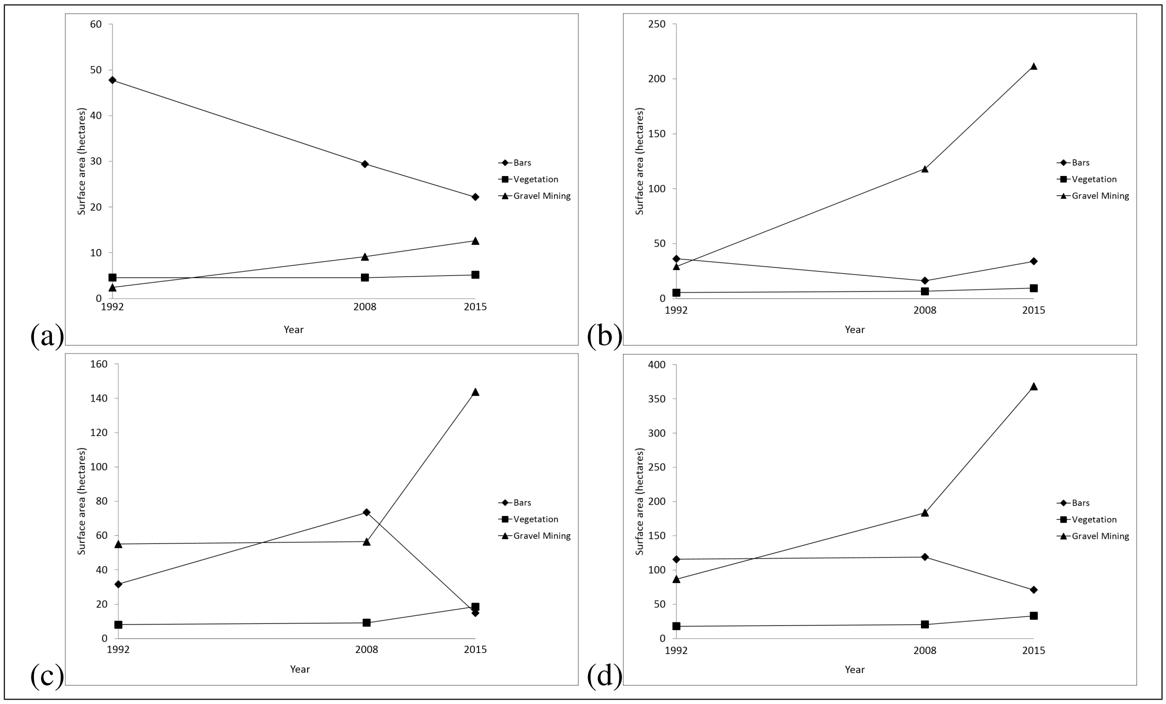


Figure 2.11. (a)−(c) Quantitative charts of land-cover evolution for sub-reach 1 (a), 2 (b), 3 (c); and the entire study reach (d). Gravel mining area increases significantly over sub-reaches 2 and 3. Sub-reach 2 shows the larger degree of intervention. Vegetation coverage remains almost constant, while bar coverage depict a slight decrease.

Sub-reach 2 exhibits again that maximum width values are given during 1980 then a strong decrease to 2007. For 2007-2009 and 2009-2011 periods, the decreasing continued, with the year 2009 having on average the lowest values of bankfull width. A small portion of sub-reach 2 in 2015 was measured with the UAV flight. Stations 2,800 to 3,800 were available showing the lowest bankfull width value for the entire series, due to gravel mining activities in both north and south banks.

Largest narrowing values were registered for stations 6400 to 6800 where 5.7 hectares of the north bank were intervened for gravel mining (Fig. 2.14b).

Sub-reach 3 shows the highest values for year 1980, and a sustained decrease in subsequent years. In this case, year 2011 shows in average the lowest values of bankfull width. Between stations 10,200 and 12,000, years 2007, 2009 and 2011 show a small narrowing trend, but past this point, narrowing becomes more evident, specifically in stations 12000 through 13000 where important gravel mining operations establish in the south bank of the river (Fig. 2.14c-d).

As in sub-reach 2, a small portion of sub-reach 3 is available through the UAV flight, where stations 10,200 to 10,600 km show a very low bankfull width for year 2015, due to heavy presence of artificial intervention (Fig. 2.14e-f).

An average width is also computed for all sub-reaches. Fig. 2.12 shows the evolution for the entire study reach. Finally, an average width difference per year rate was calculated for all periods. Between 1980 and 2007 a decrease of 18 m per year is observed, between 2007 and 2009 a decrease of 44 m per year and finally an increase of 13 m per year between 2009 and 2011. The overall trend is a decreasing bankfull width given by the increasing presence of human intervention areas (Fig. 2.17.

Figs. 2.16(a), 2.16(b), and 2.16(c) show the longitudinal profile for thalweg elevation for sub-reaches 1, 2, and 3, respectively. For sub-reach 1, year 1980 shows the highest values and subsequent years show a steady descent, with year 2011 being the lowest. For sub-reach 1, stations 2,600 and 2,800 m show the largest drop in elevation, which coincide with the construction of the Route 79 Bridge (Fig. 2.13).

For sub-reach 2, year 2011 appears as the lowest elevation profile again but with no major differences compared to year 2009. Largest differences in elevation are given at stations 4800 to 5200, which coincide with a large gravel mining sector located at the north bank (Fig. 2.15), where the increase of intervened area is evident.

Sub-reach 3 shows the most significant changes in the 1980-2000's period, showing two heavy excavation processes. Consistency between 2007, 2009, and 2011 rule out the possibility of an outlier value.

Averaging through the entire study reach, both the bankfull width and thalweg elevation show a negative trend across time (Fig. 2.17).

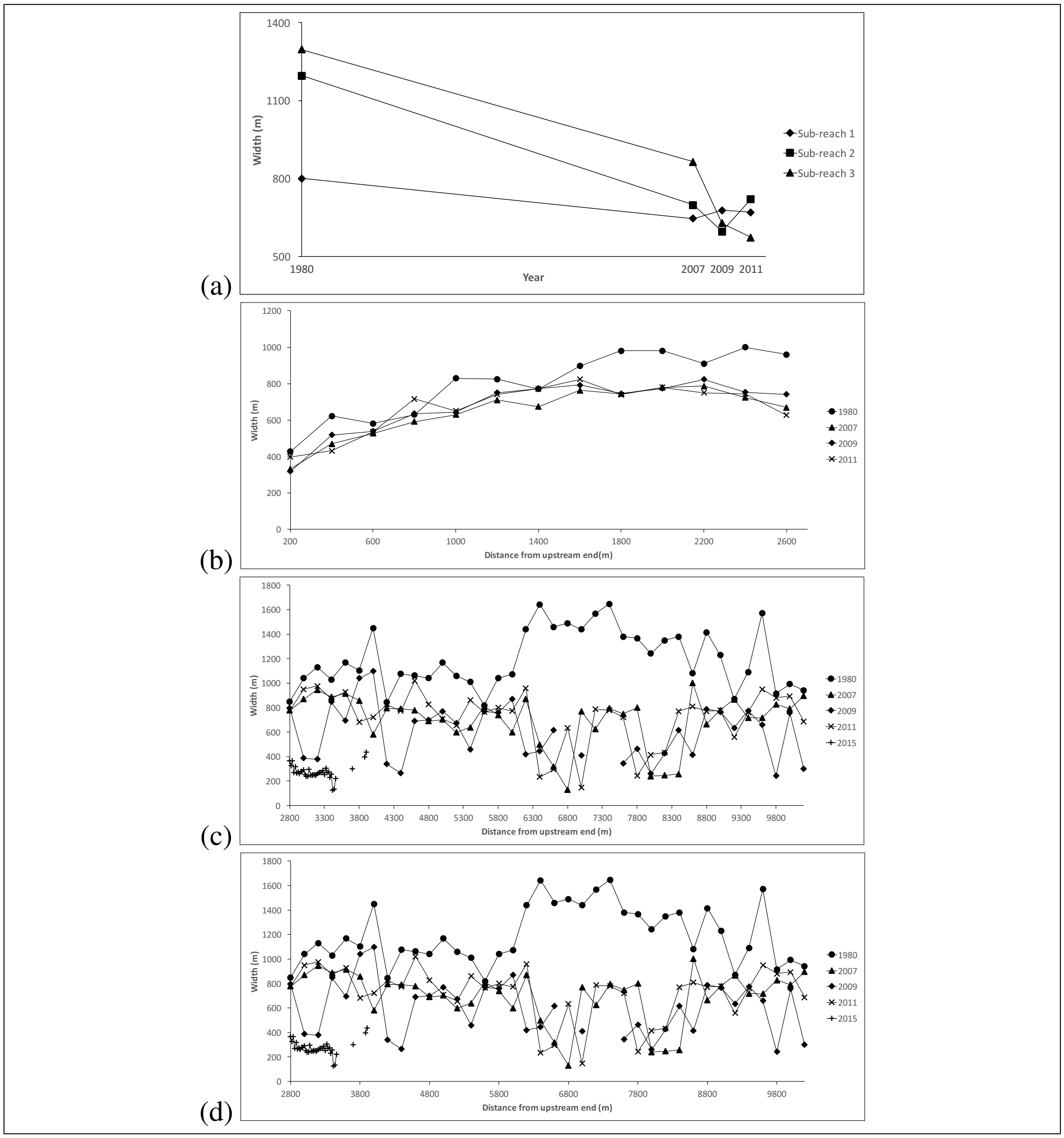


Figure 2.12. (a): Average bankfull width for the sub-reaches. (b-c-d): Bankfull width for sub-reach 1, 2 and 3 respectively.

The Difference of DEM's results are shown in Fig. 2.18, where the net difference DEM raster is present in grayscale where white tone represents aggradation and black tone erosion. In both figures the aerial photograph analysis is overlayed. Most of the dark zones of the raster coincide with the intervened polygons especially in the larger sites. The net erosion volume was computed to be 39,4 millions of m^3

Table 2.4. Difference of DEM's applied to the study reach. Computation for 1980-2011 period

	Erosion	Deposition	Net	Rate ()/per year
Area (m^2)	13,444,671	8,111,173	-5,333,498	172,048
Volume (m^3)	58,126,216	18,711,914	-39,414,302	1,271,429

2.4.3. Correlation analysis

To determine if elevation changes are related to planform changes monotonically, a correlation analysis was performed between the bed elevation and the bankfull width variation using the Spearman rank correlation function , defined as follows,

$$\rho_S = \frac{cov(r_x, r_y)}{\sigma_{r_x}\sigma_{r_y}} \tag{2.2}$$

where n pairs of variables are assigned to rankings (r_x and r_y) and a regular Pearson correlation is computed between the ranks. In our analysis, the variables were the bed elevation change $\Delta\ z_{th}$ and the bankfull width change $\Delta\ w_{BF}$. 4 series of rankings were assembled, for each registered period (1980-2007, 2007-2009, 2009-2011 and 1980-2011) in Fig. 2.17b.

The computed value of correlation is equal to $\rho_S = 0.162$ for the total cumulative change during the period from 1980 to 2011 for the full study reach, not differentiating between intervened or non-intervened zones. This magnitude of ρ_S, does not provide significant statistical association between the variables. However, the scatter plot of the thalweg change measurements vs the bankfull width change show most of the observations occupy the third quadrant (Fig. 2.17b). This result implies that large channel incisions not necessarily mean a significant narrowing, but almost every incised cross section has shown narrowing during the period of study. Correlation values are presented for each period in table 2.5.

To address the importance and influence of gravel mining, a correlation analysis was performed considering only the intervened zones (i.e: cross sections where no intervention was detected were ruled out of the analysis) of thalweg elevation variation and bankfull width variation, with computed values for Spearman and Pearson correlation of 0.56 and 0.44 respectively, showing the strong positive relationship between these phenomena when the river is intervened.

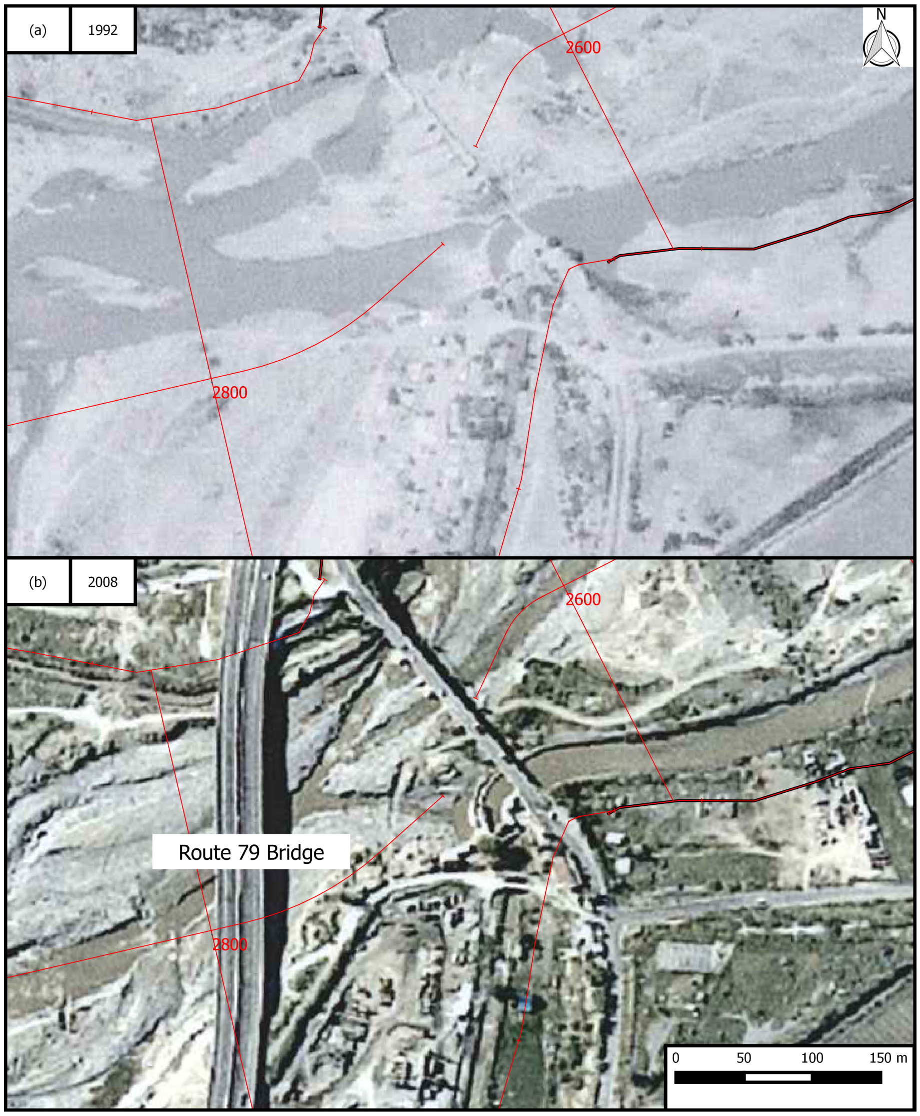


Figure 2.13. Maipo river in 1992 (a) and in 2008 (b). The photos show the effect of the construction of the Route 79 Bridge (b) on the river morphology combined with gravel mining activities.

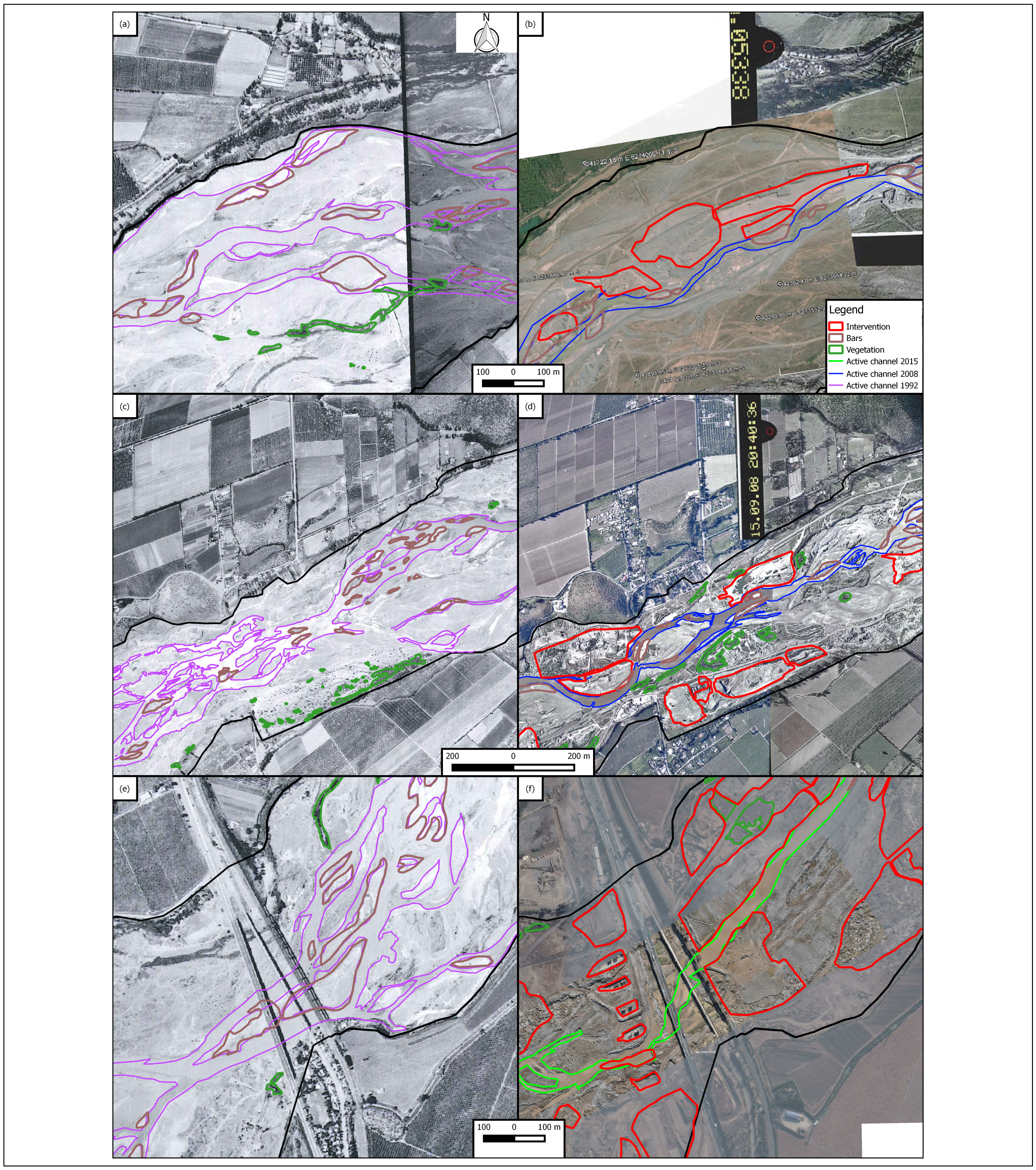
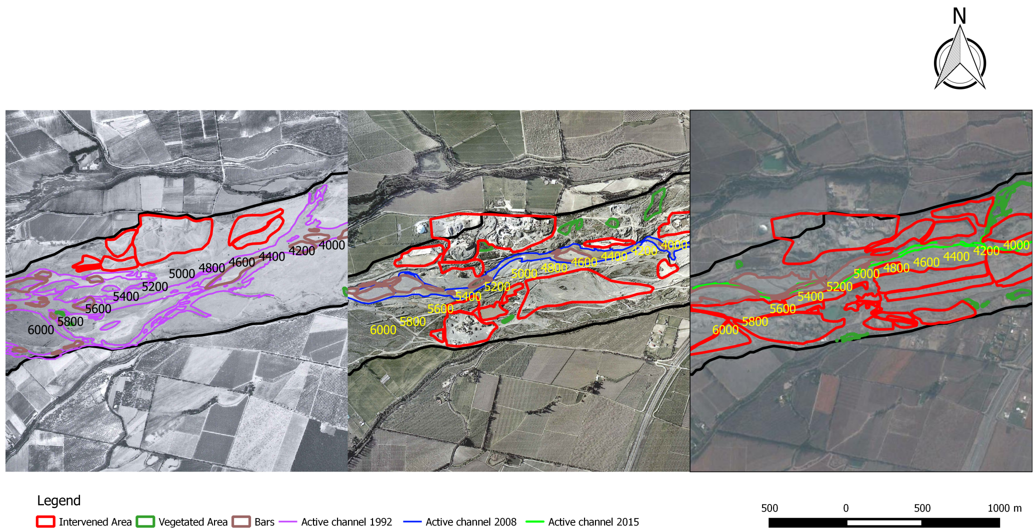
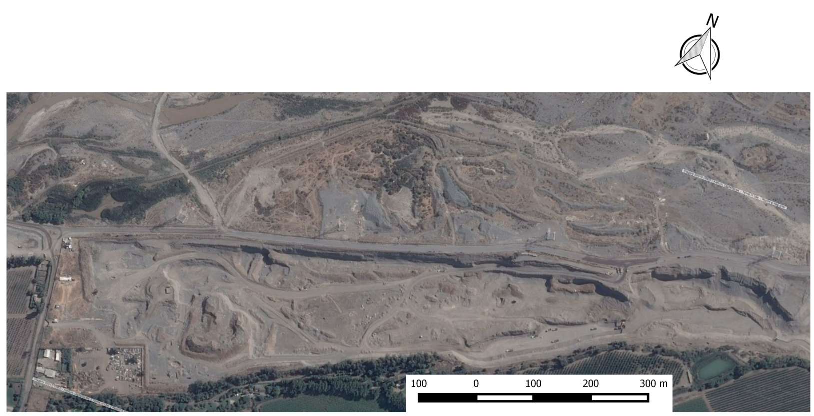


Figure 2.14. Maipo river in 1992 (a-c-e), 2008 (b-d) and 2015 (f). North bank occupied by gravel mining, moving the river active channel to the south (a-b). Mining sites of significant size appear in both north and south banks of Maipo river (c-d). Heavy intervention present due to bridge maitenance and new construction (e-f)



(a)



(b)

Figure 2.15. (a): Full evolution of a selected section of sub-reach 2 (up-stream of Route 5 bridges) from 1992 (left), to 2008 (center) and 2015 (right). Intervened areas occupy the floodplain towards the south bank. (b): Detail of the largest gravel mining site, corresponding to 2015.

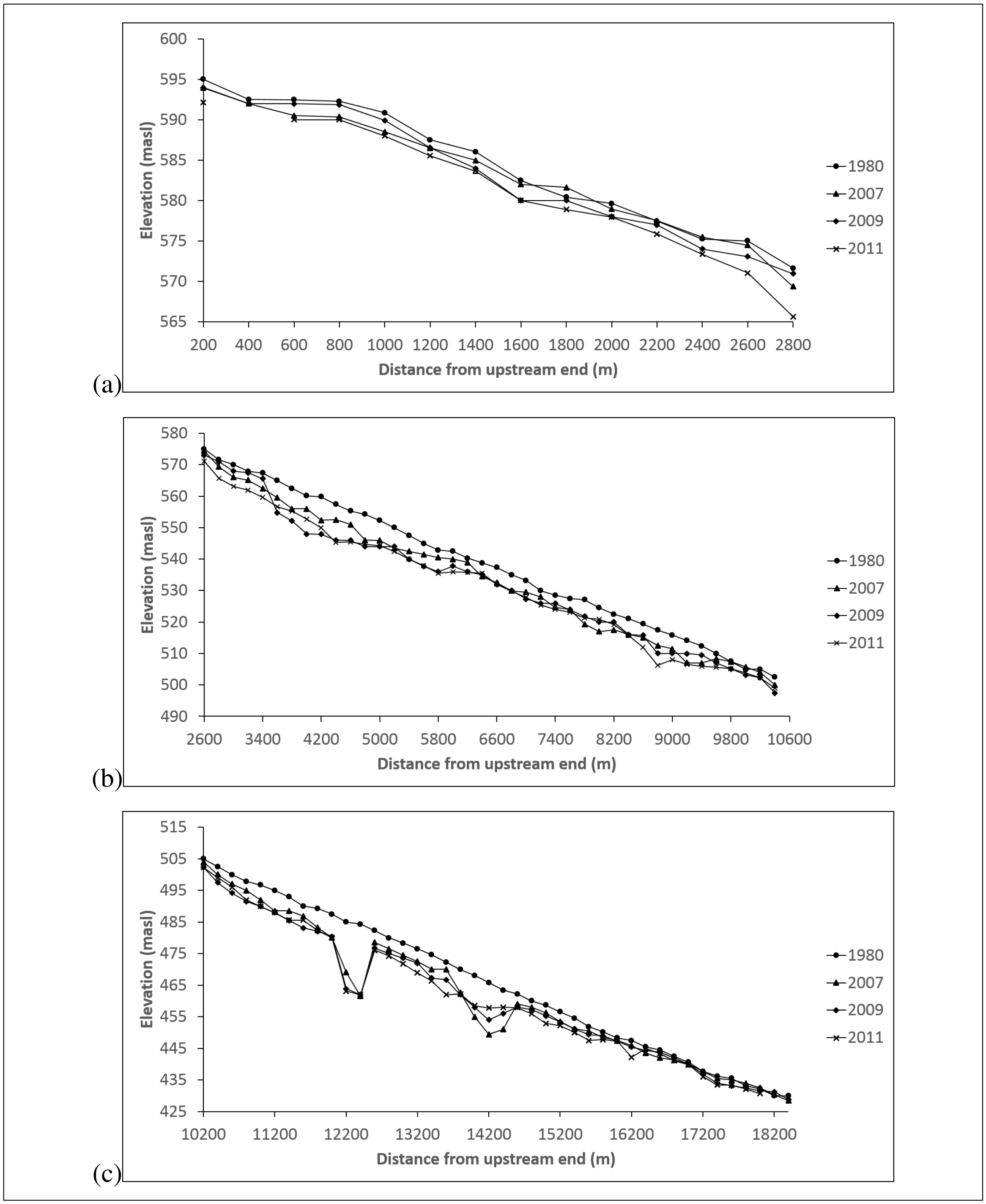


Figure 2.16. Cross section minimum elevation from 1980 to 2011 for sub-reaches 1 to 3

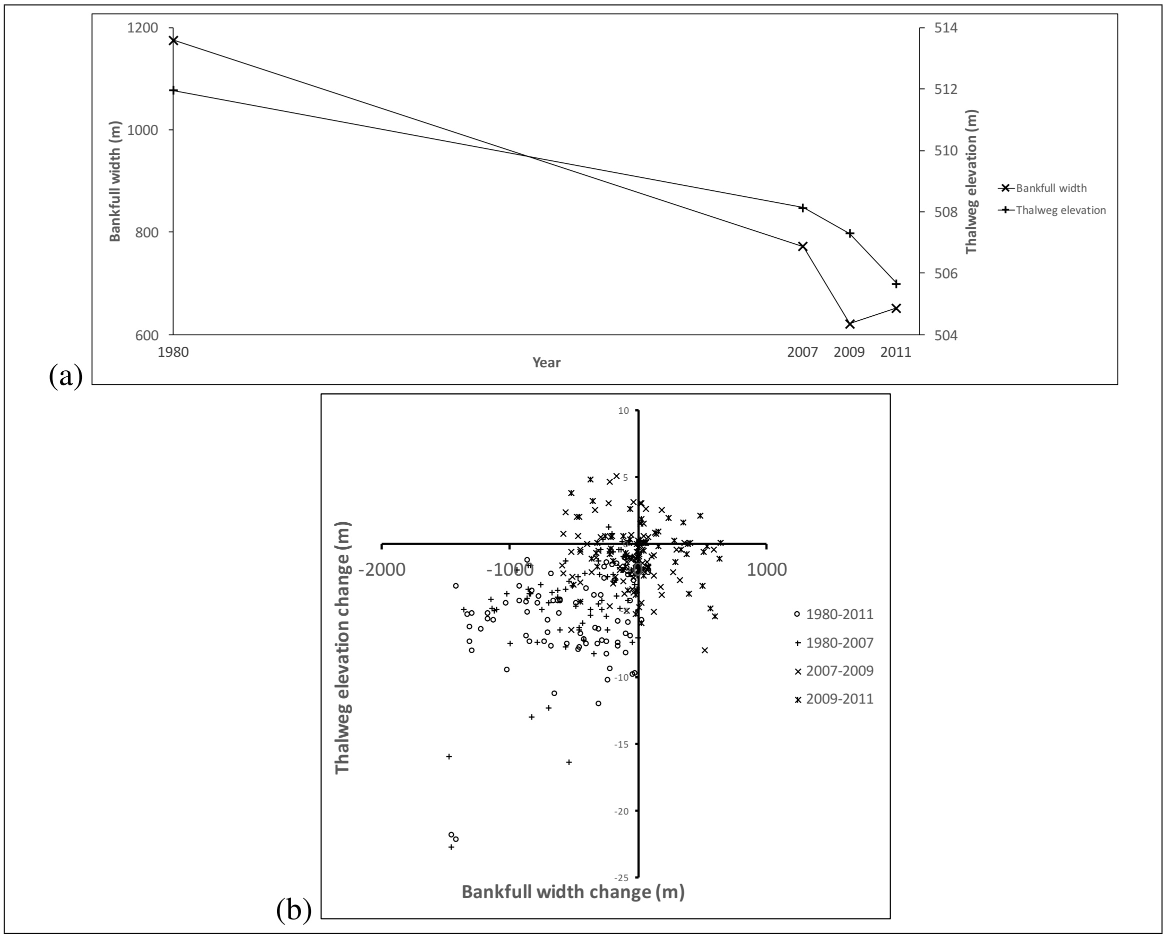


Figure 2.17. (a): Both bankfull width and thalweg elevation show a significant decrease throughout the years for the entire study reach (steep slope from 2007 to 2011). (b): Plot of elevation changes vs width changes.

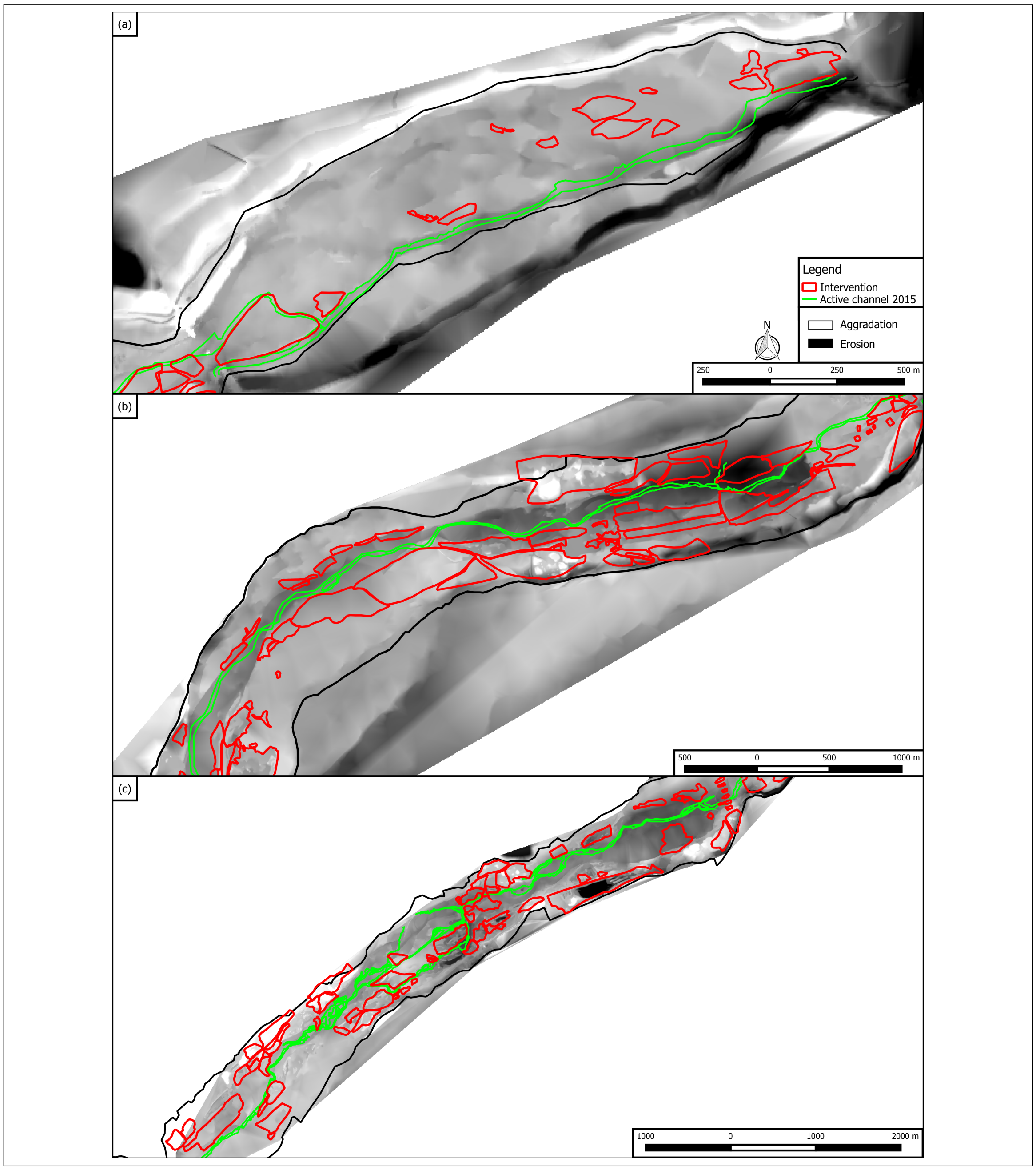


Figure 2.18. (a-c): DEM difference raster for sub-reaches 1, 2 and 3 respectively.

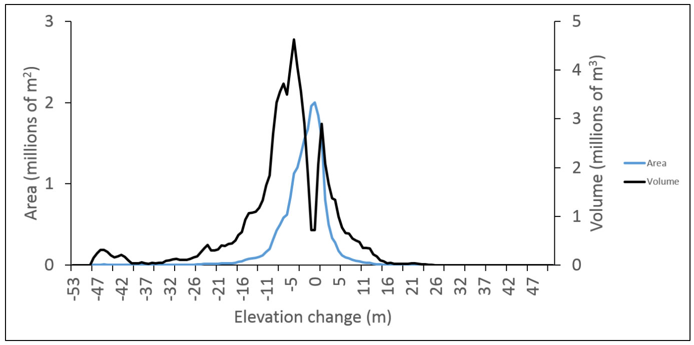


Figure 2.19. DoD results for 1980-2011 period: Total area of erosion: 1,344 hectares. Total area of deposition: 811 hectares. Net volume: -39 millions of m^3.

2.5. Discussion

2.5.1. Relation between vertical and planform changes

Between 1980 and 2007, most of the changes detected were narrowing-incisioning. Also, isolated cases of aggradation were reported which could be associated to cut and fill processes in river intervention due to bridge construction, but there is no evidence for it. Most of the narrowing-incisioning processes took place in sub-reach 2, as shown in the average bankfull width time evolution, at 1197 m to 699 m average width decrease. Spearman and Pearson correlations for narrowing and incisioning are around 0.4≈0.5 showing an evident relationship between them (Table 2.5). This trend of narrowing-incisioning is similar to the main trend of Italian, Spanish and Polish rivers that went under gravel mining (Martín-Vide et al., 2010; Rivas et al., 2006; Scorpio & Rosskopf, 2016; Surian & Rinaldi, 2003, 2004; Surian et al., 2009; Wyzga, 2007; Wyzga, B., Zawiejska, J., Radecki-Pawlik, 2014), where river channels underwent a long phase of narrowing (80%) and 8-10 m of incisioning in the case of Italian rivers and 4-5 m of incisioning at Spanish and Polish rivers. The narrowing-incisioning processes are the most intense at the initial phase (Fig. 2.17a)

Between years 2007 and 2009, all four combinations (narrowing-incision, narrowing-aggradation, widening-incision and widening-aggradation) were reported, being incision the predominant process with 51 of 75 valid measurements. Narrowing and widening processes are roughly balanced whether incision or aggradation is present, which is coherent with the low correlation values shown in table 2.5 for the 2007-2009 period. Most of the reported incisions are located in sub-reaches 2 and 3, corresponding to 22 and 21 cases respectively, out of 75 total. In total 24 out of 75 sections suffered minor aggradation on average, which corresponds to values smaller than 4 m. This stage is similar to the findings of Comiti et al. (2011), where aggradation/degradation show little to no correlation with narrowing/widening.

Between 2009 and 2011, incision again is the predominant process, with 47 of 71 valid measurements. However narrowing and widening are distributed almost equally, with 24 vs 23 measurements, explaining again the low correlation values from table 2.5 in that period. Most of the incisioning takes place in sub-reaches 2 and 3, with its mean values being the same as the 2007-2009 period. Average aggradation however decreases in sub-reaches 2 and 3. This behavior is also observed in Surian et al. (2009) and Comiti et al. (2011), where incisioning remains as the primary process while narrowing slows down or even may revert to widening (low correlation overall), as is the case for the 2009-2011 period (Fig. 2.17a-b).

Table 2.5. Correlation table for planform vs vertical changes, full study reach

	Period			
	1980-2007	2007-2009	2009-2011	1980-2011 (total)
Spearman ρ	0.443	-0.015	-0.095	0.162
Pearson ρ	0.497	-0.087	-0.238	0.114

2.5.2. River vegetation and morphological changes due to human intervention

From the analysis of the images, it is possible to determine the location and evolution of sediment bars in the sub-reaches for the entire period, as well as the vegetation covering in the vicinity of the channel. In sub-reach 1, sedimentation bars have been clearly affected by gravel mining, as bar presence dropped down as gravel mining operations increased. The correlation analysis yields a Pearson coefficient of $\rho_P = -0.98$. As the channel conveyed the flow towards the south bank, sedimentation bars present in the rest of the riverbed were exploited, extracting all the gravel that had been deposited in bars. Vegetation however did not present any considerable variations, except for some encroachment that can be noted in the last third of the reach (Fig. 2.8). Sub-reach 2 shows almost no correlation between sediment bars area and gravel mining area, with a Pearson correlation of $\rho_P = -0.09$, suggesting that in this reach new extraction sites have been established in the floodplain which is confirmed by Fig. 2.9a-c, where new sites appear close to the upstream and downstream boundaries. Fig. 2.17a supports this fact as a significant general narrowing between 1980 and 2009. Since this sub-reach is almost dry most of the time, as the entire discharge is distributed in irrigation channels, the vegetation presence is mostly confined to the river banks due to the presence of these channels. Sub-reach 3 shows a different scenario, where vegetation presence and bars have negative correlation through time ($\rho_P = -0.65$). The same happens for bars and intervened areas with a $\rho_P = -0.71$, while vegetation slightly increases with time showing positive correlation with intervened areas ($\rho_P = 0.98$).

Particularly, by analyzing only the cross sections that coincide with areas identified by air photographs, the vast majority of the intervened area presents negative change of elevation and width where the largest changes are given at sub-reaches 2 and 3, where vast extraction zones have established (Fig. 2.15). In this particular site, compared to 1980, 20 meters of depth have been lost in the floodplain and over 21 hectares of river were intervened.

As discussed previously, incision and narrowing are present mainly in sub-reaches 2 and 3, which coincides with the accelerated expansion rate of gravel mining sites (Figs. 2.9 and 2.10). Gravel mining operations have grown in the Maipo river at a significant rate and therefore river morphology has been affected by showing mostly narrowing and incisioning. In-stream mining would cause large values of thalweg elevation changes (Δz) and bankfull width values to have small variations, while river bank or floodplain extraction would cause small variations on the thalweg elevation, but increased bankfull width, producing a widening of the channel. This is supported by the photographic evidence exposed in this paper.

2.5.3. Chilean economy, social development, and gravel mining

Since the sediments extracted from the Maipo River are utilized mostly to fabricate asphalt and concrete, the degradation of the river channel can be linked with the urban growth during the period of analysis, as concrete is the most common construction material employed in the Metropolitan Region of Santiago for housing, buildings, roads, and bridges. The sediment extraction activities have modified continuously the morphology of the reach, without regulation or management strategies as no legislation is enforced for their operations. A significant volume of sediment is extracted every year at several gravel mining sites in the study reach, without any available information on the total volume. The DoD analysis yielded a total net volume of -39.41 millions of m^3 (Table 2.4, Fig. 2.19). This value is a net one calculated upon strict difference between the terrain data available. In this calculation, natural and artificial erosion-aggradation processes are involved, without the possibility of filtering gravel mining from construction intervention for example. Even though this restriction, it is possible to contemplate the significant impact done on the river and that a great part of it is due to gravel mining as shown in this research. This rate of lost volume is significantly larger than those reported by Comiti et al. (2011) (6 millions of m^3), and comparable with the rates exhibited by the Po basin (Surian & Rinaldi, 2003) with $\approx$ 3 million m^3 per year and 12 million m^3 per year at its highest rate, while the Maipo shows approximately 1.3 million m^3 per year (Table 2.4).

The census results on urban and rural population for the Metropolitan region show that urban population has experienced a steady growth, around an average of 28% annually with respect to the previous year, from 2.1 million in 1960 to 5.8 million in 2002, while rural population has remained below the 1 million mark (Fig. 2.20a). This urban population growth caused an expansion of the city urban limit (Fig. 2.20b) (INE, 2016). The image reveals that the city has experienced a significant growth in a radial direction toward rural areas, which has increased the need for infrastructure and construction materials.

This urban development is reflected by the amount of new constructions built per year (Fig. 2.20a). From 2000, the urban surface area shows a positive growth until 2006, when the subprime mortgage crisis arises in 2007 affecting the global economy situation and the amount of new construction drops. The Construction business has been proven to be intimately tied with banking and financial crisis phenomena, including Chile (Daher, 2013), which is reflected by a slow period(2006-2010). However, due to the 8.8 Richter

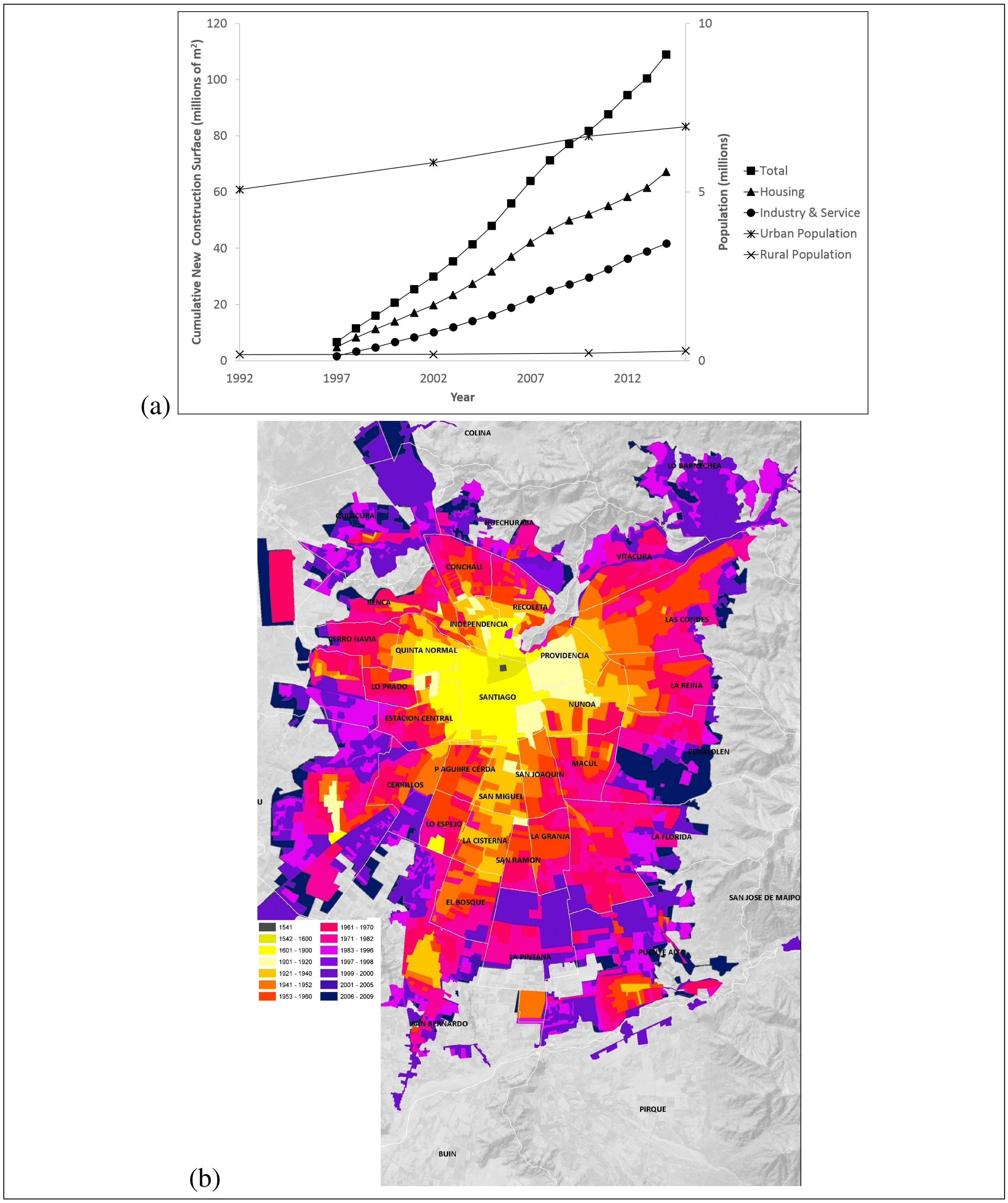


Figure 2.20. (a): Cumulative surface for new construction in the Metropolitan Region (Maipo basin). (b): Cumulative surface Urban population in Metropolitan region

earthquake in 2010, Chile suffered the destruction of 370,000 houses, 133 hospitals, 6,168 schools, and 211 bridges which required inmediate reconstruction, boosting the construction business again (even though in presence of a pessimistic global scenario) from 2010 onwards (Fig. 2.20a). These new buildings would require great quantities of construction material, so a significant increase on gravel mining activity would be expected as seen in Figs. 2.11(b-d), and the steep incision rate seen in Fig. 2.17a which reflect the steep increase in gravel mining activities on the river, reinforcing the concept. By these tokens, the demand in the construction industry can be associated with the growth of urban population and the overall economic scenario of Chile, which can be boosted by the reconstruction process that natural disasters effects trigger. While more data on volume extraction and volume of construction material would support a stronger link between urban growth and river processes as Rivas et al. (2006) where volume and surface mobilisation rates are computed and compared between river and urban development, the relationship is evident and follows the trend of Italian cases (Comiti et al., 2011; Scorpio et al., 2015; Surian & Rinaldi, 2003, 2004; Surian et al., 2009) where as long as gravel mining activities (tied up with urban growth) and the presence of dams in the river perdure, incision will.

2.5.4. Feasible alternatives for river restoration

Many alternatives exist regarding river restoration, however not all of them apply to every situation, with influencing factors such as sinuosity, urban encroachment, and available sediment load. The creation of a migration zone (a corridor for the river to flow freely) for the river is the most sustainable strategy for letting the river to "heal itself" (Kondolf, 2011), however is not always possible, specially if the stream power and sediment load is low then the restoration process can take dozens or even hundreds of years. Another possible approach to prevent and revert scouring (with satisfying results) is to widen the active channel and adding sediment to the upstream reach; by doing this, the shear stresses are reduced and so does the sediment transport capacity. This technique has been a very common measure in Austria and Switzerland, where aggradation has been measured to be of 0.75 m in the Mur river (Klösch, Hornich, Baumann, Puchner, & Habersack, 2011).

This measure would seem to fit the Maipo river, since gravel mining could be redirected into the river banks, to widen the active channel; if this could be combined with an ecological discharge from the upstream water intakes, it would allow sediment to be transported downstream and produce an aggradation process.

3. CONCLUSIONS

The Maipo river ecosystem depends on multiple factors, from the natural ones such as hydrologic dynamics (influenced by phenomena like ENSO), to the anthropic ones such as use of water resources for energy generation (with future projects upcoming such as Alto Maipo), irrigation for agriculture or drinking water supply (with increasing demand and stress over the system); and indirect uses such as riverbed exploitation by gravel mining. In this study the effect of gravel mining is assesed on an almost dry portion of the river which is left on this state due to intense water withdrawal for irrigation purposes.

This portion of the river is of vital importance due to the presence of key infrastructure located at it, such as highway bridges that connect the capital city of Santiago with the southern region of Chile representing the main ground access to the metropolis. These structures have been already affected by the evolution of the river, which can be noted at the bridges foundations, currently exposed to the surface. Other structures such as irrigation channel intakes have also been affected, requiring additional investment and more intervention on the river.

In this investigation the influence of human intervention on the river is measured and linked with the urban demographic development of the country. The focus was on measuring the effects of gravel mining with the use of aerial photographs, satellite images and topographic data taken at different years. The planform and elevation analysis yielded three important results: (1) Sustained intervention on the river has changed the morphologic parameters such as braiding index, turning the river from braided to almost single threaded (BI from 3.83 to 1.27) which are strongly linked with the correlation between narrowing and incisioning; on the other hand river sinuosity revealed no major changes overall) ; (2) the river has experienced overall narrowing and degradation due to the spreading and intensification of gravel mining activities, finding the same results as other researchers have found in Italian, Spanish and Polish rivers. This fact is proved by the considerable correlation between intervened area and bankfull width/bed elevation loss on intervention-only zones. An average of 35 cm/year of degradation and 15 m/year of narrowing of the floodplain have been measured for the study reach and the difference of DEMs yield a net loss of 39 million of m^3 between natural and artificial processes on the river from year 1980 to 2011. The most affected section of the study reach is the vicinity the bridges, where the largest sites are located, posing a great vulnerability for the infrastructure. This order of magnitude of river adjustments is similar to those found on Europe for alluvial channels, however net loss volume rate is significantly larger for the Maipo river, although a finer analysis is recommended to obtain a more precise amount that could differentiate between natural and artificial processes. (3) Gravel mining sites alone have increased their surface coverage in 325% between 2015 and 1992 (the first year available of measurements) and their growth has a visible relationship with the economic and demographic scenario in Chile, where urban population has increased in 130% and urban construction area has increased in 132%, boosted by the global construction needs in Chile. In summary, as gravel mining activities grow, the rivers turns narrower and deeper; as the Metropolitan Region increases its urban surface area along with its population, the larger amount of construction materials will be needed and gravel mining activities will in turn increase.

The Maipo river is the most important river in central Chile, that is why it is of great importance to create awareness of the need for an effective management, both in the short and the long term; not just the river as a water resource, but also as a key element of the transportation infrastructure. In river management lies the biggest challenge, since multiple users and stakeholders converge on the Maipo basin, each one with their own particular interests and conception of the river management.

4. FINAL REMARKS AND FUTURE WORK

Several potential risks associated with river intervention are in this study: (1) Given the actual trend of increasing mining activities of continuity, the risk for infrastructure failure will increase with time. With the actual degradation rates computed in this investigation, it can be expected that the foundations of the bridges installed today will continue to be exposed until structural failure is imminent, meaning the possible loss of human lives in that instant. If the appropriate authority does not take any control measures or establishes a restoration plan for the river, new bridges or repairs to the existing bridges will be needed, meaning additional public resources spent that could have been used in other contingencies if a correct river management would have allowed the river to restore itself. (2) Another latent risk is the unpredictable hydraulic behavior that the river has been left with in case of floods. Since gravel mining has spread out without control and covering both the riverbed and banks, changing the river geometry every year, in case of a flood of considerable magnitude (e.g: return period longer than 20 years) there is no certainty of the effects that the flood wave will cause on the reach and its vicinity; we cannot forget the fact that the river stays dry for the most of the time in normal conditions due to irrigation activities, so the only flow that would actually occur in the zone would be a flood, increasing the chance of more sediment removal and degradation of the reach. (3) Another potential risk is the one related to climate change and phenomena such as ENSO. As warm storms at the mountain level are more common, murky water floods are happening with more frequency and river intervention can intensify this issue, favoring the presence of suspended load and therefore increasing water turbidity, rendering the water useless for human consumption or irrigation (water intakes close up in presence of floods and water with excessive turbidity) and forcing an additional stress on the groundwater system or to suffer long service interruptions.

The challenge lying ahead is to look for an effective and sustainable management of the Maipo river. To be able to impose restriction measures on the profiting activities in a river that so important, with multiple stakeholders, legal and illegal users under a constant increase on the water supply demand. The answer is quite complex, since it has been exposed in this document (and others have described as well: Henriquez-Dole, Vicuña, and Gironas (2015); Ocampo-Melgar et al. (2016); Rosegrant et al. (2000)), the Maipo river basin administrative and jurisdictional is large and with little coordination between the users. However these last years, there has been changes towards a better communication and coordination between the stakeholders of the basin. MAPA project (for Maipo Adaptation Plan) seeks to involve the river stakeholders, along with scientists and policy makers, under a robust decision making (RDM) to work with the uncertainties that climate change and urban development scenarios, in an attempt to identify the concerns and interests of all the involved agents on the basin in a non-confrontational setting (Ocampo-Melgar et al., 2016). The lack of an integrated water-management policy poses a challenge but also a great opportunity for researchers of MAPA project to combine efforts and provide with a new insight regarding gravel mining (MAPA focused on water-resources management). The more information is gathered on the Maipo river, the better the chances of a more integrated approach for a definite management strategy for the basin. However the challenge would be still, to coordinate an integrated management of the river among all stakeholders and policy makers. A challenge that initiatives like MAPA project are currently developing and seem to be an effective way of assuring a sustainable future for the Maipo river.

REFERENCES

Alcamo, J., Doll, P., Henrichs, T., Kaspar, F., Lehner, B., Rosch, T., & Siebert, S. (2003). Global estimates of water withdrawals and availability under current and future business-as-usual conditions. *Hydrological Sciences Journal*, *48*(3), 339–348. Retrieved from http://www.tandfonline.com/doi/abs/10.1623/hysj.48.3.339.45278 doi: 10.1623/hysj.48.3.339.45278

Allan, J., Erickson, D., & Fay, J. (1997). The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biology*, *37*(1), 149–161. Retrieved from http://www-personal.umich.edu/{~}dallan/pdfs/Allan{_}et{_}al{_}1997.pdf doi: 10.1046/j.1365-2427.1997.d01-546.x

Andreoli, A., Mao, L., Iroume, A., Arumi, J. L., Nardini, A., Pizarro, R., ... Link, O. (2012). The need for a hydromorphological approach to Chilean river management. *Revista Chilena De Historia Natural*, *85*(3), 339–343.

Arnaud, F., Piegay, H., Schmitt, L., Rollet, A. J., Ferrier, V., & Beal, D. (2015). Historical geomorphic analysis (1932-2011) of a by-passed river reach in process-based restoration perspectives: The Old Rhine downstream of the Kembs diversion dam (France, Germany). *Geomorphology*, *236*, 163–177. doi: 10.1016/j.geomorph.2015.02.009

Arnell, N. W. (1999). Climate change and global water resources. *Global Environmental Change*, *9*(Supplementary), 31–49. doi: 10.1016/S0959-3780(99)00017-5

Batalla, R. J. (2003). Sediment deficit in rivers caused by dams and instream gravel mining. A review with examples from NE Spain. *Cuaternario y geomorfología*, *17*(2003), 79–91.

Belletti, B., Nardi, L., & Rinaldi, M. (2015). Diagnosing problems induced by past gravel mining and other disturbances in Southern European rivers: the Magra River, Italy. *Aquatic Sciences*, *78*(1), 107–119. doi: 10.1007/s00027-015-0440-5

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A. M., Mao, L., ... Vezza, P. (2017). Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. *Geomorphology*, *283*, 143–157. Retrieved from http://dx.doi.org/10.1016/j.geomorph.2017.01.032 doi: 10.1016/j.geomorph.2017.01.032

Biron, P. M., Buffin-B??langer, T., Larocque, M., Chon??, G., Cloutier, C. A., Ouellet, M. A., ... Eyquem, J. (2014). Freedom Space for Rivers: A Sustainable Management Approach to Enhance River Resilience. *Environmental Management*, *54*(5), 1056–1073. doi: 10.1007/s00267-014-0366-z

Bollati, I. M., Pellegrini, L., Rinaldi, M., Duci, G., & Pelfini, M. (2014). Reach-scale morphological adjustments and stages of channel evolution: The case of the Trebbia River (northern Italy). *Geomorphology*, *221*, 176–186. doi: 10.1016/j.geomorph.2014.06.007

Comiti, F., Da Canal, M., Surian, N., Mao, L., Picco, L., & Lenzi, M. (2011, jan). Channel adjustments and vegetation cover dynamics in a large gravel bed river over the last 200 years. *Geomorphology*, *125*(1), 147–159. doi: 10.1016/j.geomorph.2010.09.011

Consultores, A. I. (2009). *Estudio de Participacion Ciudadana (PAC). Diagnostico Plan Maestro Rio Maipo y Sus Afluentes, Region Metropolitana* (Tech. Rep.). Gobierno de CHile. Ministerio de Obras Publicas. Direccion de Obras Hidraulicas.

Cortés, G., Vargas, X., & McPhee, J. (2011). Climatic sensitivity of streamflow timing in the extratropical western Andes Cordillera. *Journal of Hydrology*, *405*(1-2), 93–109. doi: 10.1016/j.jhydrol.2011.05.013

Daher, A. (2013). El sector inmobiliario y las crisis económicas. *Eure*, *39*(118), 47–76. doi: 10.4067/S0250-71612013000300003

DGA Direccion General de Aguas. (2003). *Evaluacion de los recursos hidricos superficiales en la cuenca del Rio Maipo* (Tech. Rep.). Direccion General de Aguas.

Downward, S., Gurnell, A. M., & Brookes, A. (1994). *A methodology for quantifying river channel planform change using GIS.*

FAO. (2016). *Global Water Withdrawal. FAO AQUASTAT website.* Retrieved 2017-07-26, from `http://www.fao.org/nr/water/aquastat/water{_}use/`

Friend, P. F., & Sinha, R. (1993). Braiding and meandering parameters. *Geological Society, London, Special Publications*, *75*(1), 105–111. doi: 10.1144/GSL.SP.1993.075.01.05

Gaillot, S., & Piégay, H. (1999). Impact of Gravel-Mining on Stream Channel and Coastal Sediment Supply : Example of the Calvi Bay in Corsica (France). *Journal of Coastal Research*, *15*(3), 774–788.

Garreaud, R. (2013). Warm Winter Storms in Central Chile. *Journal of Hydrometeorology*, *14*(5), 1515–1534. doi: 10.1175/JHM-D-12-0135.1

Geographics, B. M. (2009). *Global Mapper Geographic Information System.*

Gleick, P. H. (1998). Water in crisis: paths to sustainable water use. *Ecological Applications*, *8*(August), 571–579. Retrieved from `http://dx.doi.org/10.1890/1051-0761(1998)008[0571:WICPTS]2.0.CO;2` doi: 10.1890/1051-0761(1998)008[0571:WICPTS]2.0.CO;2

Gob, F., Houbrechts, G., Hiver, J. M., & Petit, F. (2005). River dredging, channel dynamics and bedload transport in an incised meandering river (the River Semois, Belgium). *River Research and Applications*, *21*(7), 791–804. doi: 10.1002/rra.883

Godoy, C., Gatica, C., Niño, Y., & Mcphee, J. (2010). Towards management and regulation of gravel mining in urban areas : application of an optimization / morphological model to Maipo river. *River Flow*, 1443–1450. doi: 978-3-939230-00-7

Gregory, K., Benito, G., & Downs, P. (2008). Applying fluvial geomorphology to river channel management: Background for progress towards a palaeohydrology protocol. *Geomorphology*, *98*(1-2), 153–172. Retrieved from `http://`

linkinghub.elsevier.com/retrieve/pii/S0169555X07002139 doi: 10.1016/j.geomorph.2007.02.031

Gurnell, A. M., Downward, S. R., & Jones, R. (1994). Channel planform change on the River Dee meanders, 1876-1992. *Regulated Rivers-Research & Management*, *9*(4), 187–204. Retrieved from <GotoISI>://WOS:A1994QF56500001 doi: DOI 10.1002/rrr.3450090402

Hearne, R. R. (1981). Institutional and Organizational Arrangements for Water Markets in Chile. In K. W. Easter, M. W. Rosegrant, & A. Dinar (Eds.), *Markets for water* (pp. 141–157). Boston, MA: Springer US. doi: 10.1007/978-0-585-32088-5_9

Henriquez-Dole, L., Vicuña, S., & Gironas, J. (2015). *Gestion hidrica en la cuenca del rio Maipo: implicancia en el uso pleno de los derechos de agua.*

Hughes, M. L., McDowell, P. F., & Marcus, W. A. (2006, mar). Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology*, *74*(1-4), 1–16. doi: 10.1016/j.geomorph.2005.07.001

INE. (2016). *Estadisticas demograficas y vitales.* Retrieved 2016-09-16, from http://www.ine.cl/canales/chile{_}estadistico/familias/demograficas{_}vitales.php

James, L. A., Hodgson, M. E., Ghoshal, S., & Latiolais, M. M. (2012). Geomorphic change detection using historic maps and DEM differencing: The temporal dimension of geospatial analysis. *Geomorphology*, *137*(1), 181–198. doi: 10.1016/j.geomorph.2010.10.039

Klösch, M., Hornich, R., Baumann, N., Puchner, G., & Habersack, H. (2011). Mitigating Channel Incision Via Sediment Input and SelfInitiated Riverbank Erosion at the Mur River, Austria. *Stream Restoration in Dynamic Fluvial Systems*, 319–336.

Kondolf, G. M. (1994a). Environmental planning in regulation and management of instream gravel mining in California. *Landscape and Urban Planning*, *29*(2), 185–199.

Kondolf, G. M. (1994b). Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning*, *28*(2), 225–243.

Kondolf, G. M. (1997, jul). PROFILE: Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental management*, *21*(4), 533–51.

Kondolf, G. M. (2011). Setting Goals in River Restoration:When and Where Can the River "Heal Itself"? In *Stream restoration in dynamic fluvial systems* (pp. 29–43). doi: 10.1007/s13398-014-0173-7.2

Kondolf, G. M., & Larson, M. (1995). Historical channel analysis and its application to riparian and aquatic habitat restoration. *Aquatic conservation: Marine and freshwater ecosystems*, *5*(January), 109–126.

Kondolf, G. M., Piégay, H., & Landon, N. (2007). Changes in the riparian zone of the lower Eygues River, France, since 1830. *Landscape Ecology*, *22*(3), 367–384. doi: 10.1007/s10980-006-9033-y

Lane, S. N., Westaway, R. M., & Hicks, D. M. (2003). Estimation of erosion and deposition volumes in a large , gravel-bed , braided river using synoptic remote sensing. *Earth Surface Processes and Landforms*, *28*(3), 249–271. doi: 10.1002/esp.483

Leopold, L. B., & Wolman, G. (1957). *River channel patterns braided, meandering and straight.*

Little, P. J., Richardson, J. S., & Alila, Y. (2013). Geomorphology Channel and landscape dynamics in the alluvial forest mosaic of the Carmanah River valley , British Columbia , Canada. *Geomorphology*, *202*, 86–100. doi: 10.1016/j.geomorph.2013.04.006

Martín-Vide, J., Ferrer-Boix, C., & Ollero, A. (2010, may). Incision due to gravel mining:

Modeling a case study from the Gállego River, Spain. *Geomorphology*, *117*(3-4), 261–271. doi: 10.1016/j.geomorph.2009.01.019

Mertes, L. a. K. (2002). Remote sensing of riverine landscapes. *Freshwater Biology*, *47*(4), 799–816. doi: 10.1046/j.1365-2427.2002.00909.x

Milan, D. J., Heritage, G. L., Large, A. R. G., & Fuller, I. C. (2011). Filtering spatial error from DEMs: Implications for morphological change estimation. *Geomorphology*, *125*(1), 160–171. doi: 10.1016/j.geomorph.2010.09.012

Nations, U. (2014). World Urbanization Prospects: The 2014 Revision, Highlights. *Population Division, United Nations*, 32. Retrieved from `http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf` doi: 10.4054/DemRes.2005.12.9

Ocampo-Melgar, A., Vicuña, S., Gironás, J., Varady, R. G., & Scott, C. A. (2016). Scientists, Policymakers, and Stakeholders Plan for Climate Change: A Promising Approach in Chile's Maipo Basin. *Environment: Science and Policy for Sustainable Development*, *58*(5), 24–37. doi: 10.1080/00139157.2016.1209004

Palmer, M. A., Reidy Liermann, C. A., Nilsson, C., Flörke, M., Alcamo, J., Lake, P. S., & Bond, N. (2008). Climate change and the world's river basins: Anticipating management options. *Frontiers in Ecology and the Environment*, *6*(2), 81–89. doi: 10.1890/060148

Petit, F., Poinsart, D., & Bravard, J.-P. (1996). Channel incision , gravel mining and bedload transport in the Rhone river upstream of Lyon , France ("canal de Miribel"). *Catena*, *26*(3), 209–226.

Piegay, H., Cuaz, M., Javelle, E., & Mandier, P. (1997). Bank erosion management based on geomorphological, ecological and economic criteria on the Galaure River, France. *Regulated Rivers-Research & Management*, *13*(5), 433–448. doi: doi: 10.1002/(SICI)1099-1646(199709/10)13:5%3C433::AID-RRR467%3E3.0.CO;2-L

Poff, N. L., Allan, J. D., Palmer, M. A., Hart, D. D., Richter, B. D., Arthington, A. H., … Stanford, J. A. (2003). River flows and water wars: emerging science for environmental decision making. … *and the Environment*, *1*(6), 298–306. doi: 10.1890/1540-9295(2003)001[0298:rfawwe]2.0.co;2

Rinaldi, M., Surian, N., Comiti, F., & Bussettini, M. (2015). A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. *Geomorphology*, *251*, 122–136. Retrieved from `http://www.sciencedirect.com/science/article/pii/S0169555X15002640` doi: 10.1016/j.geomorph.2015.05.010

Rinaldi, M., Wyzga, B., & Surian, N. (2005). Sediment mining in alluvial channels: Physical effects and management perspectives. *River Research and Applications*, *21*(7), 805–828. doi: 10.1002/rra.884

Rivas, V., Cendrero, A., Hurtado, M., Cabral, M., Giménez, J., Forte, L., … Becker, A. (2006). Geomorphic consequences of urban development and mining activities; an analysis of study areas in Spain and Argentina. *Geomorphology*, *73*(3-4), 185–206. doi: 10.1016/j.geomorph.2005.08.006

Rosegrant, M., Ringler, C., McKinney, D., Cai, X., Keller, A., & Donoso, G. (2000). Integrated economic-hydrologic water modeling at the basin scale: The Maipo river basin. *Agricultural economics*, *24*(63), 33–46. doi: 10.1016/S0169-5150(00)00113-4

Scorpio, V., Aucelli, P. P., Giano, S. I., Pisano, L., Robustelli, G., Rosskopf, C. M., & Schiattarella, M. (2015). River channel adjustments in Southern Italy over the past 150years and implications for channel recovery. *Geomorphology*, *251*, 77–90. doi: 10.1016/j.geomorph.2015.07.008

Scorpio, V., & Rosskopf, C. M. (2016). Channel adjustments in a Mediterranean river over the last 150 years in the context of anthropic and natural controls. *Geomorphology*, *275*, 90–104. doi: 10.1016/j.geomorph.2016.09.017

Sepulveda, S. A., Rebolledo, S., & Vargas, G. (2006). Recent catastrophic debris flows in Chile : Geological hazard , climatic relationships and human response. *Quaternary International*, *158*(1), 83–95.

Sernageomin. (2016). *Registro de principales desastres en Chile desde 1980* (Tech. Rep.). Sernageomin. Gobierno de Chile.

Surian, N., & Rinaldi, M. (2003, mar). Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology*, *50*(4), 307–326. doi: 10.1016/S0169-555X(02)00219-2

Surian, N., & Rinaldi, M. (2004). Channel adjustments in response to human alteration of sediment fluxes : examples from Italian rivers. *IAHS Publication*, *288*(August), 276–282.

Surian, N., Rinaldi, M., Pellegrini, L., Audisio, C., Maraga, F., Teruggi, L., & Ziliani, L. (2009). Channel adjustments in northern and central Italy over the last 200 years. *Geological Society of America Special Papers*, *80301*(451), 83–95. doi: 10.1130/2009.2451(05).

Sowik, M. (2015). Is history of rivers important in restoration projects? The example of human impact on a lowland river valley (the Obra River, Poland). *Geomorphology*, *251*, 50–63. Retrieved from `http://linkinghub.elsevier.com/retrieve/pii/S0169555X15003281` doi: 10.1016/j.geomorph.2015.05.031

Vorosmarty, C. J., Green, P., Salisbury, J., & Lammers, R. (2000). Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science*, *289*(5477), 284–288. Retrieved from `http://www.sciencemag.org/cgi/doi/10.1126/science.289.5477.284` doi: 10.1126/science.289.5477.284

Warner, R. F. (2012). Environmental impacts of hydroelectric power and other anthropogenic developments on the hydromorphology and ecology of the Durance channel and the Etang de Berre, southeast France. *Journal of Environmental Management*, *104*, 35–50. doi: 10.1016/j.jenvman.2012.03.011

Wheaton, J. M., Brasington, J., Darby, S. E., & Sear, D. A. (2009). Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms*, *156*(December 2009), n/a–n/a. doi: 10.1002/esp.1886

Wishart, D., Warburton, J., & Bracken, L. (2008). Gravel extraction and planform change in a wandering gravel-bed river: The River Wear, Northern England. *Geomorphology*, *94*(1-2), 131–152. Retrieved from `<GotoISI>://WOS:000252829200010` doi: DOI 10.1016/j.geomorph.2007.05.003

Wyzga, B. (2007). A review on channel incision in the Polish Carpathian rivers during the 20th century. *Developments in Earth Surface Processes*, *11*(07), 525–553. doi: 10.1016/S0928-2025(07)11142-1

Wyzga, B., Zawiejska, J., Radecki-Pawlik, A. (2014). Impact of channel incision on the hydraulics of flood flows : Examples from Polish Carpathian rivers. *Geomorphology*, *272*, 10–20. doi: 10.1016/j.geomorph.2015.05.017

Zanoni, L., Gurnell, A., Drake, N., & Surian, N. (2008). Island dynamics in a braided river from analysis of historical maps and air photographs. *River Research and Applications*, *24*(8), 1141–1159. doi: 10.1002/rra

Zawiejska, J., Wyga, B., & Radecki-Pawlik, A. (2015). Variation in surface bed material along a mountain river modified by gravel extraction and channelization, the Czarny Dunajec, Polish Carpathians. *Geomorphology*, *231*, 353–366. doi: 10.1016/j.geomorph.2014.12.026

Ziliani, L., & Surian, N. (2012). Evolutionary trajectory of channel morphology and controlling factors in a large gravel-bed river. *Geomorphology*, *173-174*, 104–117. doi: 10.1016/j.geomorph.2012.06.001