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Abstract: During the 1970s, the Palancia River was intensively affected by gravel mining instream. This activity completely destroyed the fluvial forms, devastating the original wandering pattern. At the end of the 1980s, gravel mining ceased and the river started a process of recovery, only altered by several maintenance and cleaning operations. The aim of this work is to describe these processes of change analyzing the river's morphosedimentary conditions, through a GIS analysis of aerial photographs previous, simultaneous and subsequent to the intense gravel mining activity. Results show the current difficulties of some ephemeral rivers to restore their original forms, because of the sediment and water deficit conditions, the critical role of incision, and the development of inadequate actions of river restoration and channelization for flood prevention.

Highlights

We analyzed the evolution of an ephemeral river which was devastated by gravel mining.

We used a synthetic index for the spatio-temporal assessment of channel forms recovery.

Sediment and water deficit conditions determined the process of recovery.

Incision has played a major role in the distribution and intensity of the process of recovery.

Dry periods stimulated vegetation encroachment processes.

Clearing and maintenance actions hindered the spontaneous process of recovery.

CHANNEL FORMS RECOVERY IN AN EPHEMERAL RIVER AFTER GRAVEL MINING (PALANCIA RIVER, EASTERN SPAIN)

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ABSTRACT

During the 1970s, the Palancia River was intensively affected by gravel mining instream. This activity completely destroyed the fluvial forms, devastating the original wandering pattern. At the end of the 1980s, gravel mining ceased and the river started a process of recovery, only altered by several clearing operations. The aim of this work is to describe these processes of change analyzing the river's morphosedimentary conditions, through a GIS analysis of aerial photographs previous, simultaneous and subsequent to the intense gravel mining activity. Results ~~show~~ the current difficulties of some ephemeral rivers to recover their original forms, because of the sediment and water deficit conditions, the critical role of channel incision and ~~the development of~~ inadequate actions of river clearing and channelization for flood prevention.

KEY WORDS: Ephemeral rivers; river trajectories; sediments; gravel mining; channel forms; incision; land use changes.

INTRODUCTION

Human activity has played a major role in the historical evolution of rivers, causing contrasting and frequently overlapping effects. However, during the last 70 years, scientific literature shows a predominance of actions converging in the same direction, causing sediment deficit in many rivers of the world. Anthropogenic activities such as gravel mining (Rinaldi *et al.*, 2005), dam construction (Surian, 1999; Brandt, 2000; Batalla *et al.*, 2003; Batalla, *et al.* 2006; Graf, 2006; Ma *et al.*, 2012; Rollet *et al.*, 2014; Lobera *et al.* 2015), torrent control works (Boix-Fayos *et al.*, 2007, Castillo *et al.*, 2007), river channelization (Winterbottom, 2000; Sipos *et al.*, 2007; Ollero, 2010; Arnaud *et al.*, 2015), and combinations of these processes (Rinaldi, 2003; Preciso *et al.*, 2012, Ollero *et al.*, 2015), have severely affected sediment availability, generating the well-known *hungry waters* effect (Kondolf, 1997). This effect is also frequently stimulated by natural or human-induced reforestation processes (Lach and Wyzga, 2002; Keestra *et al.* 2005, Begueria *et al.*, 2006), which facilitate sediment retention in headwater areas. In many cases, these processes have taken place in parallel to various long-term hydroclimatic fluctuations (Benito *et al.*, 2008; Church, 2008; Glaser *et al.*, 2010).

Sediment deficit result~~s~~ in significant morphological changes in rivers. River incision, lateral channel instability, bed armouring and channel narrowing are common effects that have been identified in numerous European rivers (Bravard *et al.*, 1999; Liébault and Piégay, 2002; Kondolf *et al.*, 2002; Batalla, 2003; Wyzga, 2008; Rinaldi *et al.* 2005; Martín-Vide *et al.*, 2010; Surian and Rinaldi, 2003; Surian and Cissotto, 2007; Wishart et al., 2008; Surian et al., 2009). Vegetation encroachment processes are interwoven with these changes, through complex interactions between the colonisation of vegetation, river morphology and morphodynamics (Gurnell et al, 2001, 2009, 2012; Surian et al., 2015; Gumiero et al., 2015; Dufour et al., 2015; Picco et al. 2016, 2017).

These processes of morphological change can produce a wide range of environmental and social effects, such as the undermining of infrastructures (Kondolf, 1997), loss of habitat diversity (Bravard *et al.*, 1999; Nakamura *et al.*, 2008) or coastal erosion (Gaillot and Piégay, 1999). For these reasons the analysis of the historical change of river forms has caught the attention of many authors, reporting numerous case studies (Comiti *et al.* 2011; Ziliani and Surian, 2012; Rădoane *et al.*, 2013; Magdaleno *et al.*, 2014; Scorpio *et al.*, 2015; David *et al.*, 2016; Magliulo *et al.*, 2016), mainly based on the interpretation of aerial photographs, satellite imagery and analogic cartographic sources. Although ephemeral rivers' dynamics and responses to floods are well-known (Merritt and Wohl, 2003; Hooke and Mant, 2000; 2002; Ortega *et al.*, 2014; Calle *et al.*, 2015) scarce attention has been paid to their historical evolution (Segura-Beltrán and Sanchis-Ibor, 2013; Calle *et al.*, 2017). These fluvial systems are particularly interesting because the intermittent connection between river basin and channel provide a specific framework for river adjustment process in response to environmental changes and human impacts.

~~In t~~his paper ~~we~~ analyze the evolution of an ephemeral river located in Eastern Spain (the Palancia River), whose channel forms have been devastated by gravel mining and maintenance works. The principal aims of this paper are: i) to reconstruct channel changes during the last 70 years; ii) to assess the relationship between channel adjustments, natural changes and human disturbances at channel and basin scale; iii) to identify channel recovery patterns after the devastation caused by gravel mining; and iv) to assess the self-restoration potential of the river reach, highlighting implications for channel restoration in ephemeral rivers.

STUDY AREA

The Palancia River is located between the Castelló and València provinces (Eastern Spain). It is 85 km long and drains a 910 km^2 basin. The river valley is located between the Calderona and Espadà mountains, with a typical Iberian orientation (NW-SE). The Iberian mountain range was folded during the paroxysmal compressive phase in the Oligocene, when anticlinal and synclinal structures with a NW–SE orientation ~~were~~ formed during the Alpine orogene. After this phase, a compressive Miocene phase generated a series of folds transverse to the Iberian trend. Later, two distensive phases occurred at the end of the Tertiary and the beginning of the Quaternary, generating horsts and grabens transverse (NE-SW) to the Iberian folds (Figure 1). The river flows through these trenches, and in the coastal plain has formed a large quaternary alluvial fan, which overlaps tertiary detritic sediments (Pérez Cueva, 1989).

The river basin is under the influence of a Mediterranean climate, with mean annual rainfall ranging from 510 mm at the headwaters to 410 mm in Sagunt. At the headwaters the river is semi-perennial, with flow provided by local perched aquifers. The Regajo dam (6.6 Mm^3) has regulated the ~~headwaters~~ flow since 1959 (mean river flow is 1.3 m^3/s) and supplies the irrigation canals of the coastal plain (Figure 1).

Downstream of the dam, the river becomes ephemeral in its last 25 km, and only carries continuous flow after heavy rains. The Palancia River has recurrent flash floods and the flow dynamics are similar to ~~the~~ Mediterranean wadis or *ramblas* (Segura, 1990; Camarasa and Segura-Beltrán, 2001). At the lower river reach, the channel sediment is mainly bedload of medium size, coble and gravels (40-80 mm of diameter) (Nacher-Rodriguez et al., 2013). The Algar reservoir (6 Mm^3), located just upstream of the study area, was built in 2000 in order to control floods and to recharge the coastal plain aquifer. It is always empty due to impounded area permeability.

In the Palancia basin, evolution of the land cover pattern has followed similar trends to other areas in the region (Pascual Aguilar, 2002; Segura-Beltrán and Sanchis-Ibor, 2013). Population, agricultural (mainly citriculture) and urban land uses have increased during the 20th century in the coastal plain areas of the Palancia basin, around the city of Sagunt. In the headwaters and mountainous areas, ~~processes of~~ depopulation ha~~ve~~ led to the abandonment of agriculture and the regeneration of vegetation, which has taken place spontaneously in most areas and has been stimulated by reforestation operations in others.

Gravel extractions intensively affected the Palancia River during the 1970s and 1980s, as occurred to other rivers in Spain (Mas-Pla *et al.*, 1999; Uribelarrea *et al.*, 2003; Rovira *et al.*, 2005; Martín-Vide *et al.*, 2010). Original river forms were completely destroyed. However, at the end of the 1980s, this activity was limited by the basin authority (Confederación Hidrográfica del Júcar, CHJ). Gravel extraction was forbidden in the lower reach (study area), but permitted in some tributaries of the intermediate basin. Consequently, the lower river reach started a spontaneous process of recovery, only altered by some maintenance and clearing operations. This recovery process took place in a context of sediment deficit, also induced by the aforementioned land use changes and reservoir construction.

The study area is located in the lower ephemeral reach of the Palancia River, between the Alfara ford and the river mouth (Figure 1). It is 21.3 km long and it has a confined section upstream of the city of Sagunt, becoming semi-confined downstream of this point. La Sarba Ravine (32 km^2) is the only relevant tributary at this reach, although other small torrents flow into ~~this river reach~~. During the first half of the 20th century, the study area had a wandering pattern, with an increasing number of bars, islands and secondary channels towards the lower sectors. In the following decades, channels forms were substantially altered.

MATERIALS AND METHODS

Assessment of channel changes

River channel changes between 1946 and 2012 were assessed through aerial photograph interpretation. Images from 1946, 1956, 1977, 1988 and 1991 (Table 1) were scanned at a resolution 400 dpi and georectified through a second order polynomial through ArcGIS TM version 9.3 (ESRI, Redlands, California, 2009). Oblique aerial photographs taken from an airplane, immediately after the October 2000 flood, were also rectified through the same method. In order to reduce distortions in rectification as much as possible, the smaller scale images were cut in several pieces and rectified separately. Ground control points were selected only in areas close to the river channel. Root mean square errors were provided by ArcGIS software after rectification, with mean values for each date ranging between 0.26-0.92.

Orthoimages were obtained from the Valencian Institute of Cartography (ICV) (from 2000, 2004 and 2006) and the National Center of Geographic Information (CNIG) (from 2012). The most recent image was used as base layer for georeferencing the aerial photographs and to digitize the river forms in a unique layer (shapefile format). The maps of the official Land Registry of 1930 (Dirección General del Catastro), developed at 1:2.000 scale, were also georeferenced to digit~~al~~ize the river banks in the study area in order to compare the results with the first aerial image (1946).

Table 1. Characteristics of the images used.

Date	**Type**	**Scale**	**Agency**	**Pixel size (m)**	**Film and Color**	**Mean RMS Error (m)**
1930	Map	1/2,000	Land Registry Office	0.25		2.93
1946	Aerial photograph	1/43,000	Ministry of Defense (CECAF)	1	Panchromatic Black-and-white	0.81
1956	Aerial photograph	1/33,333	Ministry of Defense (CECAF)	1.15	Panchromatic Black-and-white	0.80
February 1977	Aerial photograph	1/18,000	Ministry of Agriculture (IRYDA)	0.60	Panchromatic Black-and-white	0.92
September 1988	Aerial photograph	1/5,000	Valencia Regional Government (GVA)	0.50	Panchromatic Black-and-white	0.26
March 1991	Aerial photograph	1/25,000	Valencia Regional Government (GVA)	0.85	Panchromatic Black-and-white	0.78
August 2000	Ortophoto	1/20,000	Valencian Institute of Cartography (ICV)	0.50	Digital color	
October 2000	Oblique aerial photo	Not uniform	Department of Geography, Universitat de València	0.50	Color	0.51
May 2004	Ortophoto	1/20,000	Valencian Institute of Cartography (ICV)	0.50	Digital color	
July 2006	Ortophoto	1/5,000	Valencian Institute of Cartography (ICV)	0.50	Digital color	
2009	Ortophoto	1/5,000	National Center of Geographic Information (CNIG)	0.25	Digital color	
2012	Ortophoto	1/5,000	National Center of Geographic Information (CNIG)	0.25	Digital color	

The study area was divided into 6 reaches (*a* to *f*) that represent relatively homogeneous sections of the river corridor (Figure 1 and Table 2), according to physiographic criteria (river corridor width, slope, confinement and human pressures). The river corridor was identified as the area ~~being part of~~ the total active channel area (TA) at least during one of the study periods (Belletti et al., 2015). TA excluded permanently cultivated and urbanized areas.

Table 2. Study area reaches characteristics and criteria of division

	Initial (1946) confinement	*River corridor Width*	*Slope ($^{0}/_{00}$)*	*Human pressure*
a	Confined	Narrow (146 m)	7.2	Low
b	Confined	Wide (254 m)	6.2	Medium
c	Confined	Narrow (134 m)	6.1	Medium
d	Semi-confined	Wide (213 m)	0.3	Medium
e	Semi-channelized	Narrow (135 m)	6.5	High
f	Unconfined	Wide (225 m)	5.5	High

Measuring river planform changes in an ephemeral stream imposes several methodological difficulties, due to the lack of permanent flow. Therefore, in this study, river form measurements ~~have been~~ calculated considering all the channels, bars and islands discernible in the dry TA. In three aerial pictures (1977, 1991 and 2004) some parts of the channels had some pools or intermittent shallow water, which did not completely occupy the dry channels. ~~We have considered~~ these elements as a part of the gravel channel. Thus, the gravel channel (GC) included both dry and temporarily wet areas of the channels, something unavoidable in ephemeral streams. The active channel (AC) included the area occupied by the GC and bare sediments.

Channel forms were classified following a modification of the conceptual models of Gurnell et al. (2001), Zanoni et al. (2008), Garófano-Gómez et al. (2013) and Segura-Beltran and Sanchis-Ibor (2013), and adapted to the particular ephemeral conditions of this river. We distinguished between (i) gravel channels, unvegetated branches of the river bed (ii) unvegetated bars, (iii) sparsely vegetated areas, such as incipient islands and lateral deposits covered by herbs and scattered bush (<5%), (iv) densely vegetated areas, covered by bushes and trees, v) agricultural lands, and vi) artificially leveled areas, such as paved or gravel-mined areas. The minimum patch size established to individualize bars and islands was 50 m^2. We mapped and measured the resulting areas for each aerial photograph through ArcGIS TM version 9.3.

In order to assess the evolution of the channel pattern during the entire study period, we modified the fuzzy kappa statistic (Garófano-Gómez *et al.*, 2013). With the information obtained from each pair of maps, we built fuzzy matrixes applying the mentioned classification of channel forms (Table 3). Changes in ascending order according to this classification (from less-vegetated ~~categories~~ to most-vegetated or artificialized) correspond to active channel narrowing trajectories or floodplain constructive processes, whereas changes in descending order indicate channel widening or floodplain destruction processes. Stable forms configure a diagonal in the matrix that separates both trajectories. The resulting matrix permits assessment and quantification of the prevailing trajectories between each pair of aerial photographs, as shown in the results section.

Table 3. Matrix for the calculation of prevailing trajectories

	Gravel channel	*Unvegetated bars*	*Barely vegetated*	*Densely Vegetated*	*Artificialized*	
Gravel Channel	**Stable**	Gravel channel to Unvegetated bars	Gravel channel to Barely vegetated	Gravel channel to Densely vegetated	Gravel channel to Artificialized	***Channel narrowing and floodplain construction***
Unvegetated bars	Unvegetated bars to Gravel channel	**Stable**	Unvegetated bars to Barely vegetated	Unvegetated bars to Densely vegetated	Unvegetated bars to Artificialized	
Barely Vegetated	Barely vegetated to Gravel channel	Barely vegetated to Unvegetated bars	**Stable**	Barely vegetated to Densely vegetated	Barely vegetated to Artificialized	
Densely vegetated	Densely vegetated to Gravel channel	Densely vegetated to Unvegetated bars	Densely vegetated to Barely vegetated	**Stable**	Densely vegetated to Artificialized	
Artificialized	Artificialized to Gravel channel	Artificialized to Unvegetated bars	Artificialized to Barely vegetated	Artificialized to Densely vegetated	**Stable**	
	Channel widening and floodplain destruction					

In order to assess the changes in the gravel channel in terms of width, length and number of branches, we used ArcGIS TM version 9.3 to calculate the channel width, the channel count index (BI_{T3}) and the total sinuosity index (P_T). BI_{T3} (Howard et al., 1970; Egozi and Ashmore, 2008) consists of the mean number of channel segments (N_L) intersected by cross-sections (X_S) of the river. P_T is the result of dividing the total length of channels (ΣL_L) per unit length of river (Lr) (Hong and Davies, 1979; Richards, 1982). For these sorts of measurements, some studies suggest using a distance between cross-sections which is equal or lower than channel width (Egozi and Ashmore, 2008), and for this purpose channel width can be measured using the ratio channel area/reach length (58.8 m in this case, not considering 1977 because of massive river form destruction). Consequently, measures were taken in 425 cross sections along the study reach, separated by 50 m. Channel width was estimated in all these cross sections for each one of the study periods.

Channel incision was measured indirectly from a DEM ~~5 m pixel size~~ generated with 2009 LiDAR data from the National Plan of Aerial Orthophotography (PNOA, www.cnig.es). Incision was calculated for the period 1946-2009 through the identification of the micro-terraces generated by lateral channel migration (Segura-Beltran and Sanchis-Ibor, 2013) in 87 cross sections (equidistant 250 m). The necessary condition for selection was the identification of sections where the active corridor had narrowed since 1946. These calculations were only feasible in 29 of the 87 reaches, because in the other 56 it was impossible to recognize any micro-terrace correctly. Stereoscopic analysis of the 1946 aerial photographs, some historical pictures, and fieldwork contributed to corroborate the information provided by DEM analysis in some of these sections.

In order to integrate all the above data, we performed a morphological recovery index (MRI) to analyze and compare the changes of the river forms in the different sectors of the study reach. This MRI is a combination of the GC width, the AC area, the P_T and the BI_{T3}. To calculate the MRI, we expressed these four parameters in percentages from 100% (maximum value) to 0% (minimum value), and then we obtained the average of the four parameters. Results were performed and expressed through a color map similar to the Channel Complexity Index (CCI) developed by Llena *et al.* (2016), respecting the proportions of the spatial and time axis. We used this sort of graphic expression to combine our results with other variables (channelization works, flood events and incision), in order to develop a cross-analysis in the discussion section.

Assessment of natural and human factors

Hydrological changes. Information on flood series was obtained from two gauging stations that register mean daily flows: Sot de Ferrer and Fuente del Baño (Figure 1). Both are located upstream of the study area (26 km and 7 km respectively). They cover different periods and have unequal drainage basins. Data from Sot de Ferrer (659 km^2) was used for the period 1914-1943 and it represents the natural river flow. In the Sot de Ferrer series, floods between 1914 and 1920 could have been undervalued because some event days are missing. Similarly, flooding for the period between 1930 and 1946 is likely to be underestimated because there was no data for the period 1933-1942. Fuente del Baño station (478 km^2) data was used for the period 1945-2010. Between 1945-1955 the river flow was undisturbed, while between 1959-2010 the regime was altered by the construction of the Regajo dam (6 Mm^3) immediately upstream of the station. In both gauging stations we have calculated the number and volume of flood events. In order to compare the two sets of gauging data, several unit flow parameters (annual flow volume and annual maximum peak) have been estimated by dividing flow data ~~and~~ respective drainage basin areas. Information on the impact and flooded area of the events of 1957 and 1962 was obtained from a report by the Ministry of Public Works (MOP, 1963). No data on sediment transport upstream and downstream of the dam was available. Some information on the volume of sediments stored in the reservoir was derived from the studies carried out by Cobo (2008).

Land use changes. We mapped land use changes in the Palancia River basin between 1956 and 2009. Aerial photographs dating from 1946, 1956, 1977 and 1991 (Table 1) and an ortophoto dating from 2009 (IGN) were used to map the whole Palancia basin through ArcGIS TM version 9.3 (ESRI, Redlands, California, 2009). We defined nine land use types for classification: (i) urban areas; (ii) forested areas (>50% of forest strata coverage); (iii) bush or shrub areas; (iv) rainfed annual crops; (v) irrigated trees, mainly citriculture; (vi) rainfed cultivated trees; (vii) sparsely vegetated areas, also including small bare rock patches and recently burnt areas; (viii) river beds; and (ix) reservoirs and ponds.

Information on gravel mining instream, channelization and refurbishment actions was obtained from the Jucar basin authority (CHJ), various field visits and aerial photographs, including some series not used for channel form classification, dating from

1938 (Ufizzio Storico dell'Aeronautica Militare Italiana), 1976 (CHJ), 1983 (Diputació de València), 1987 (GV), 1995 (GV) and 1997 (ICV).

RESULTS

Natural and human-induced changes in basin and river conditions

Gravel mining, reservoirs and refurbishment works. The first evidence of gravel mining in the Palancia river dates back to 1938. Aerial pictures taken by the Italian bombers during the Civil War show several small and scattered sites of gravel extraction close to Sagunt city, in sectors *d* and *e*. We also detected these manual extractions in the aerial pictures of 1956, when these small pits become particularly concentrated in sector *d*.

Industrial extractions took place during the decades of 1960 and 1970, when several companies obtained licenses from the basin authority. The CHJ was interested in deepening the river bed to reduce the impact of floods in the Sagunt area so it neither controlled nor limited the extraction activities. There w~~as~~ no data ~~avalaible~~ regarding extractions made during the 1960s and 1970s. The aerial photographs of 1977 show the river bed completely devastated by gravel mining throughout the whole study area. In these pictures, no fluvial forms are recognizable, and the entire river bed consists of gravel pits and dumped mounds.

In 1980s, the CHJ estimated the volume of extractions to be 68,000 m^3. Since 1981 mining markedly decreased, oscillating between 10,000 and 20,000 m^3 until 1988, when this activity ceased. The latest aerial picture in which we recognize instream gravel mining activity dates back to 1987. The total volume extracted during the period 1980-1988 is 137,925 m^3 (Pardo, 1991), but according to the affected area observed in aerial pictures, ~~we understand that~~ the amount of sediment removed during the decade of 1970 must have been much higher. CHJ data also show~~s~~ 49,764 m^3 of sediments extracted between 2000 and 2007. However, this activity did not directly impact on the study area, because it was developed in the tributary river, Rambla de Azuébar, upstream from the Algar reservoir.

Reservoirs also caused sediment retention. The impact of Regajo reservoir has been estimated to be 326,000 m^3 between 1959 and 2007 (Cobo, 2008). No estimation has been calculated for the Algar reservoir, which was built in 2000 but it is not yet fully operative.

Channelization, dredging and clearing operations also took place in the river during the study period. The first intervention was developed at the beginning of the 1950s, affecting the river reach located between Sagunt and the river mouth (Sector *f*). It consisted of a 50m wide channel dredged as an artificial talweg at the center of the channel section, destroying the original wandering pattern.

Between 1992 and 1995 the CHJ redeveloped this intervention in the same area. This time the river was also leveled and cleared with bulldozers to remove vegetation between Sagunt and the Estivella Weir (Sectors *b*, *c*, *d*, *e*, *f* and the lower part of *a*). This process was repeated in the same area in the spring and summer of 2000, to keep the riverbed clear. The most recent intervention, advertised as an "environmental improvement" by the administration, took place between 2009 and 2011 downstream of Sagunt. It affected most parts of sector *f*, consisted of clearing and gardening works, and constructing protection for bridge footings against incision.

Land use changes. The overall trend of the study period (1946-2009) is increased reforestation (Figure 2). Annual crops, mainly located in the headwaters and middle area, clearly decreased (from 8,403 to 4,901 ha), resulting in increased forest and bush. The overall forests area more than quadrupled in size, from 5,346 to 23,548 ha. Although the quantity of bush appears to be stable or slightly decreasing throughout the study period, (from 47,945 to 43,387 ha), a detailed analysis through fuzzy matrix calculation shows that site specific changes have taken place. Bush behaves as a transitional stage between the cultivated areas and the new forests. Tree crops have a similar behavior. Rainfed trees markedly decreased but citriculture expanded in the low valley, resulting in a slight total decrease for tree crops from 30,807 to 19,760 ha between 1946 and 2009. Thus, to sum up, most of land use change trends suggest a moderate change in runoff, reducing the impact of rainfall on flow and sediment generation.

Hydrological changes. Flow data analysis shows significant changes throughout the 20th century, both in discharge and flood frequency and magnitude. The annual unit flow volume has decreased by 36.3%. It was 0.11 Mm^3/km^2 in the natural regime (Sot de Ferrer) and 0.07 Mm^3/ km^2 for the altered flow in Fuente del Baño. Mean annual maximum daily flows also decreased from 38.34 m^3/s (0.06 $m^3/s/km^2$) in the natural regime (Sot de Ferrer) to 9.86 m^3/s (0.02 $m^3/s/km^2$) in the altered regime (Fuente del Baño). In this case, the presence of the dam explains the drastic reduction of 64.25%.

The annual unit discharge has decreased throughout the twentieth century, both due to natural and human factors. Figure 3 shows that the annual unit discharge in natural regimes ha~~ve~~ decreased exponentially, both between the period 1917-1942 (Sot de Ferrer) and between 1946-1957 (Fuente del Baño), which is solely due to natural factors. The altered unit discharge between 1956 and 2011 does not show a clear trend, since it is controlled by the dam.

Analysis of the flood data shows different behavior between the period 1912-1930 and the period 1930-2010 (Figure 3). In 18 years, 44 flood events were registered, whereas in the following 80 years only 28 were recorded (Figure 3). Flood events were particularly frequent between 1920 and 1930. The highest registered event, the December 1920 flood, accumulated 220 Mm^3 in Sot de Ferrer, and in the same hydrological year 124 Mm^3 was recorded in February 1921 at the same gauging station.

Flood frequency decreased considerably during the second half of the 20th century. This was corroborated by other results obtained in the region, which show very similar flood series. The secondary peak of the century (1956-1977) observed in the Palancia River, was also observed by Segura and Sanchis (2013) at the Rambla de Cervera and Cervol basins. However, in this case, this trend could have been altered by the construction of the Regajo Reservoir (1959), which has partially mitigated the impact of floods in the medium and low Palancia valley. However, the Regajo reservoir does not prevent large flash flood development (Camarasa and Segura, 2001), because the watershed located downstream of the dam is large enough to generate these events.

In the period simultaneous or subsequent to gravel mining development, flood frequency was also ~~scarce,~~ particularly after 1978. Three significant events took place (Figure 4). [illegible]t, the flood of December 1971~~, with~~ a daily maximum discharge of 49.87 m^3/s (at Fuente del Baño). Second, after the dry period of 1978-1986, the flood of 1989, with a peak of 35.8 m^3/s, slightly higher than the 1988 flood (29.6 m^3/s). Third, after the dry period 1991-1999, the flood of October 2000, ~~with~~ an estimated peak of 101.35 m^3/s at Fuente del Baño and 362.8 m^3/s at Algar de Palancia (Segura and Sanchis, 2011), just upstream of the starting point of the study area.

Changes in the Palancia river corridor

Evolution of channel forms. Channel morphology has considerably changed over the study period. In 1946, the river showed a widening pattern. ~~The~~ comparison of the information provided by the 1930 Land Registry and the 1946 and 1956 pictures shows a river ~~which~~ is slightly moving its corridor, destroying small cultivated areas beyond the river banks. These processes were still in progress in the lowest part of the sector *f* in the flood of 1962. After this event, no natural widening processes were detected.

In 1946, the gravel channel and the unvegetated bars occupied respectively 25% and 30% of the river corridor, whereas the densely vegetated areas plus the cultivated lands (part of them located in islands) did not exceed 15% of the study area (Figure 5). Results from 1956 photo-interpretation show similar figures, but with a significant increase of the barely vegetated areas accounting for up to 50% of the river corridor. These forms were severely altered by gravel mining during the 1970s. The 1977 aerial photograph shows more than 65% of the river corridor occupied by gravel mines. The existence of natural or semi-natural river forms was then merely residual.

~~In~~ 1988, the river had started a morphological recovery process. The gravel channel expanded from 6% to 17% of the river corridor, and herbaceous vegetation colonized half of the study reach (50%). These trends slightly increased in the three following years, reaching 22% and 53% respectively in 1991. The trajectory of recovery was subsequently altered. The aerial picture taken in August 2000 shows the river following a large maintenance and clearing project developed by the CHJ, which levelled and artificialized more than 50% of the river corridor (Figure 5).

After the flood of October 2000, river forms were regenerated, even though they did not achieve similar values to those of 1946. The gravel channel achieved the maximum area of the study period (30%) in October 2000, but the unvegetated gravel bars only reached 8%. Since 2000, the gravel channel has decreased up to 18% and vegetation colonization processes and artificial levelling have continued (Figure 5).

Predominant river trajectories. Fuzzy matrices (Figure 6) provide detailed information on river adjustment trajectories. Stable forms draw a diagonal line separating floodplain constructive (above) and destructive changes among the different categories (below). Figure 6 summarizes the changes that took place during the study period. Different trajectories have been identified:

- In the period 1946-1956 we observe a mixed pattern. Vegetation encroachment clearly progressed over the unvegetated bars, but at the same time, some cultivated islands and point-bars were incorporated into the active corridor. Widening changes slightly prevail.

- Artificialization clearly prevailed when gravel mining or clearing operation took place (1956-1977 and 1991-2000BF).

- Widening processes predominated immediately after the artificialization stages (1977-1988 and 2000BF-2000PF), when the active channel was reconstructed by floods, destroying both mined and vegetated areas.

- Narrowing processes prevailed in two periods (1988-2000BF and 2000PF-2012), following both channel widening stages, after the initial reconstruction of the gravel channel.

- Stable forms had a positive balance during the whole study period, from 33% in 1946-1956 to 77% in 2006-2012. This reflects the preeminence of the narrowing processes that prevailed in most of the stages, consolidating stable forms at the river banks, attached to the floodplain.

Changes in the wandering pattern. We assessed the evolution of the gravel channel pattern through the calculation of the channel count index and total sinuosity index. Mean values have significant oscillations, according to the consecutive degradation and recovery stages of the Palancia River (Figure 7).

Both indexes decrease between 1946 and 1977. After 1977, both the number of channels and their length increased, and in 1991 reached similar figures to 1946. Table 4 shows an interesting contrast along the river between 1988 and 1991. ~~In~~ 1988, when the channel recovery process ~~had barely started~~, BI_{T3} and P_T ha~~ve~~ significantly increased in sectors *b* and *c*, but this increase is much less evident downstream from this area. However, in 1991, the recovery process had progressed enough to recover the gravel channel forms also in the lowest river reach.

In the summer of 2000 the river forms had been ~~newly homogenized~~, but the post-flood aerial picture shows the fluvial forms again regenerated (Figure 7). Both BI_{T3} and P_T increased, but after 2004 started a decreasing trend. This behavior is particularly evident in wide sections such as *b* and *d* (Table 4).

Table 4. Main results per sectors. Gravel Channel (GC) width in meters; Active Channel (AC) area in percentage on each sector area; Channel count index (BI_{T3}); and Sinuosity index (P_T).

		1946	1956	1977	1988	1991	2000 BF	2000 PF	2004	2006	2012
a	GC Width	38.4	30.9	25.8	30.3	29.1	30.5	40.9	34.0	31.6	30.9
	AC Area	40.8	22.5	16.1	26.3	25.2	22.4	34.5	26.2	24.0	22.9
	BI_{T3}	1.2	1.2	1.0	1.3	1.2	1.1	1.3	1.2	1.2	1.1
	P_T	1.4	1.4	1.0	1.4	1.3	1.1	1,5	1,4	1,3	1,3
b	GC Width	30.1	55.7	34.9	45.0	46.8	38.9	85.8	79.0	45.4	36.9
	AC Area	39.1	24.5	3.5	19.0	21.9	9.3	42.7	33.6	18.6	15.1
	BI_{T3}	1.7	1.6	0.2	1.7	1.8	1.1	1.8	1.2	1.1	1.1

	P_T	2.0	1.8	0.2	2.2	2.5	0.4	2.1	1.5	1.1	1.1
c	GC Width	27.1	39.7	6.5	47.5	46.6	17.7	81.4	50.0	46.0	36.0
	AC Area	57.1	41.2	0.4	35.8	37.2	2.7	59.7	36.3	29.6	23.9
	BI_{T3}	1.1	1.1	0.0	1.6	1.7	1.1	1.1	1.1	1.1	1.1
	P_T	1.2	1.2	0.0	1.8	1.8	0.7	1.1	1.0	1.0	1.0
d	GC Width	40.8	38.0	0.0	31.9	85.4	2.5	98.6	79.1	73.0	37.6
	AC Area	58.5	21.4	0.0	15.7	52.8	0.4	77.4	38.7	6.5	8.8
	BI_{T3}	1.4	1.3	0.0	1.1	1.5	1.0	2.1	1.9	0.2	0.5
	P_T	1.3	1.3	0.0	1.0	2.1	0.2	2.2	2.2	0.2	0.5
e	GC Width	42.6	33.3	23.4	23.8	32.6	32.5	58.8	40.5	34.9	38.8
	AC Area	10.5	33.0	12.9	15.5	21.9	8.1	48.1	29.0	18.9	18.3
	BI_{T3}	1.2	1.2	0.8	0.9	1.1	1.1	1.2	1.2	0.5	0.8
	P_T	1.2	1.1	0.8	0.9	1.1	0.4	1.3	1.3	1.1	1.0
f	GC Width	59.8	66.0	20.5	42.6	43.7	26.4	47.0	47.1	34.2	30.6
	AC Area	89.2	31.9	0.8	11.9	23.6	12.1	34.8	35.2	33.2	25.6
	BI_{T3}	1.9	1.1	0.1	0.7	1.3	1.0	1.7	1.7	1.6	0.5
	P_T	1.9	1.1	0.1	0.6	1.4	1.0	1.6	1.8	1.6	1.0

Channel incision. The comparison of the 1946 microterraces level with the current river thalweg shows important differences in 29 cross sections of the Palancia river. Figure 8 shows two different patterns, one located at the confined and semi-confined area of the study reach (upstream of Pedres Blaves Weir), and another at the (originally) non-confined area. Mean incision has been estimated to be 2.4 m in the upper section (reaches *a, b, c* and *d*) and 5.6 m in the lower section (reaches *e* and *f*).

There are also significant differences in the lower reach. Incision clearly progresses from the river mouth, and reaches its maximum value in a knickpoint caused by a calcareous crust outcrop (Figure 8). Upstream of this site, incision is smaller until the Pedres Blaves Weir, close to where it reaches 6.7 m. Incision progressing from the river mouth is also observed in the recurrent damages to the bridges located downstream the Pedres Blaves Weir (Railway Bridge and CV-3201 Bridge in Figure 8). Their footings have been artificially protected to defend against undermining processes. The Pedres Blaves concrete weir is acting as a barrier for incision, protecting upstream areas.

The marked incision pattern of the lower sector of the river has also been detected in other works. Segura-Beltrán *et al.* (2012) compared two ~~DEM-~~LiDAR models from 2003 and 2009, and observed a significant incision in the whole channel downstream from the abovementioned calcareous crust nickpoint. However, upstream from this point, incision is concentrated only in the river talweg, while lateral bars and microterraces moderately develop.

DISCUSSION

Conceptual model of evolution

Numerous Mediterranean rivers have experienced the impact of gravel mining, dam building, channelization works and reforestation processes throughout the 20th century. In the most recent decades adjustment processes have taken place in these fluvial systems adapting river~~s~~ morphology to these new environmental conditions, consisting mainly ~~in~~ river incision, channel narrowing and decreases in braiding intensity. In some perennial gravel-bed rivers, particularly in Italy, recent widening or stabilization trends have been detected after several decades of adjustment (Comiti *et al.*, 2011; Ziliani and Surian, 2012; Bollati *et al.*, 2014; Clerici *et al.*, 2015; Scorpio *et al.*, 2015).

However, the Palancia River still remains in a clear adjustment stage. There is neither evidence of stabilization nor signs of a forthcoming trend reversal. This can be attributed to two facts. First, to the particular behavior of ephemeral rivers, where adjustment processes slow down due to the intermittence of the connection between the river channel and the sediment sources. Second, to the particular intensity and recurrence of human interference in this river channel and basin, which has markedly altered and interrupted the adjustment processes. In order to investigate these processes further, we have developed a cross-analysis of the different variables considered in the results section, distinguishing six different stages in the recent evolution of the Palancia River forms (Figure 9).

Aggradational stage (1946-1956). The Palancia River presented a clear aggradational pattern during this period, with a marked morphological diversity. According to the comparison of the 1930 Land Registry maps and the aerial pictures of 1946 and 1956, floods were still widening the river corridor throughout this period. In the absence of in-stream direct human impacts such as gravel mining or reservoirs, the river wandering pattern and the active channel area achieved the maximum mean values of the whole study period. This trend is similar to other European rivers, and it is also related to the intensive use of hillsides for cattle and agriculture during the first half of the 20th century (Surian, 1999; Liébault *et al*. 2005; Beguería *et al*. 2006; Segura-Beltrán and Sanchis-Ibor, 2013; Scorpio *et al*., 2015; Magliulo *et al*., 2016).

In this stage, the morphological diversity seems to be proportional to the river corridor width: the wider sectors of the river corridor (*b*, *d* and *f*) have the highest MRI (Figure 9). The lack of effective floods between 1946 and 1956 explains the slight decrease of the morphological indicators between these dates. Moreover, ~~the~~ channelization of the lower area substantially simplified river forms in sector *f* in 1956.

Intense gravel mining stage (1956-1988). According to the 1977 aerial p~~icture~~, gravel mining completely devastated river forms between 1956 and 1988. Despite the significant number and magnitude of floods during this period, persistent instream human operations destroyed the river bars, islands and channels, preventing river forms from recovering.

First recovery (1988-1992). The prohibition of gravel mining works in the study area gave the river an opportunity to partially reconstruct its former wandering pattern. The small floods of 1987 and 1988 contributed to the recovery of some of these fluvial forms, as observed in the September 1988 aerial picture. Figure 9 shows how this initial recovery process was limited to the sectors located in the confined area (*a*,*b*,*c*,*d*), without a significant impact in the lower and unconfined area (*f*), where the morphological indicators remained below the values of 1956.

However, the floods of 1989 and 1990 were more effective, and boosted the recovery process in these lower sectors. These floods had no significant impact on the fluvial forms of the narrow confined sector (*a*), where the river forms had been previously reconstructed, but increased the morphological diversity in the rest of the river channel. It is important to highlight that, in this period, the Sinuosity index (P_T) reached its maximum value (2.5 in sector *b*; Table 4). This unusual pattern can be attributed to the disturbance created by the remaining gravel accumulations and pits (more frequent in this reach), which altered the hydraulic conditions of the river channel and forced the flow to follow unexpected curves, creating narrow and highly sinuous secondary channels.

Channelization stage (1992-September 2000). Between 1992 and the summer of 2000, the Basin Authority (CHJ) conducted several clearing and flattening operations throughout most of the study area. Channel forms were again devastated and MRI reached the lowest values across all of the sectors (Figure 9).

Second recovery (October 2000-2004). The large flood of October 2000 regenerated the river forms, recovering the wandering pattern. Mean sinuosity and channel count indexes reached similar levels to the aggradational stage, and channel width exceeded the 1946 values.

Despite the magnitude of this event, the river was not capable of completely restoring the level of morphological complexity it had prior to the devastation caused by gravel mining. This is particularly relevant in the lowest reach (*f*), where the river had achieved the maximum MRI in 1946 (Figure 9). However, at the confined sectors the MRI reached levels closer to the 1946 values. Two factors seem to cause this behavior:

i) All river reaches were affected by a deficit of sediments due to the combined effect of gravel mining, sediment retention in reservoirs and basin reforestation. These factors limited the amount of sediment~~s~~ available to recuperate the river forms in the whole study reach. This hungry water~~s~~ effect, visible in the artificial knickpoints detected ~~in~~ several bridges (Figure 8), also explains the fact that the AC area (Figure 5) is the only parameter of the MRI that remained below the values of the aggradational period in this second recovery stage. Even immediately after the large flood of 2000, the Palancia River has not had enough sediment to restore the original large unvegetated bars, which were particularly frequent in sector *f* in 1946.

ii) The role played by incision in channel narrowing is critical to explain the lower recovery rate of the unconfined sector (*f*). The deep incision levels in the Palencia River are similar to values observed by Martín-Vide et al. (2010) and Tuset et al. (2015) in other areas of the Iberian Peninsula in similar contexts. As ~~we have detected~~ in other cases in the region (Segura-Beltrán and Sanchis-Ibor, 2013), river incision causes a concentration of flow and erosion in the thalweg area, partially protecting lateral micro-terraces from the impact of floods. This process enhances incision in the gravel channel and leaves lateral vegetated islands as raised micro-terraces, partially unconnected to sedimentary changes. This process has taken place in both confined and semiconfined areas, but it is particularly intensive where incision has been more prominent and the channel is wide enough to preserve lateral micro-terraces (reach *f*). Figure 10 shows this process. The river had a clear wandering pattern in 1946. After the two stages of artificialization, both recovery processes (1991 and 2000pf) took place in a context of sediment deficit. Incision created a longitudinal scarp that facilitated flow concentration into a deeper section, also stimulating vegetation encroachment during the last decade. Moreover, incision processes reduced the impact of floods on the floodplain. While the floods of the 1930s, 1957 and 1962 generated overbank flow over the agricultural and urban areas at the southern bank of the river (at the lower part of sector *f*), the subsequent floods (such as the extraordinary event of 2000) have not affected any areas beyond the river corridor.

Recent vegetation encroachment (2004-2012). The second stage of recovery was followed by a process of vegetation encroachment, which occurred after 2004, when the river basin went through a dry period. The lack of relevant floods stimulated vegetation colonization from the sparsely vegetated areas towards the gravel channel (Figures 9 and 10). If we compare vegetation encroachment with incision and river corridor width we observe that this process has been particularly intense in the wide areas of the confined sectors with low incision (sectors b and d). In these reaches, the flat topography of the river corridor causes the dissipation of the river flow, reducing the erosional processes. Vegetation has narrowed the gravel channel in these areas, completely interrupting the continuity of the channel, which vanishes in some points (Figure 10).

In the lower river reach (*f*), the so-called “environmental improvement” developed by the CHJ in 2009 substantially worsened the morphological diversity of the river corridor. This operation, together with the clearing and flattening works developed between 1992 and 2000, clearly interfered with the river adjustment trends and damaged the river ecosystem’s integrity by destroying the river’s semi-natural morphology.

Adjustment and river forms recovery in ephemeral streams

Since 1988, after gravel mining was banned in the study area, the river has been following a trajectory of recovery, adjusting the channel planform to new basin conditions. This recovery trend has been affected by several restriction factors. The first is the water and sediment deficit, caused by hydro-climatic factors, land use changes, sediment retention in reservoirs and past in-stream gravel mining.

The second restriction is water and sediment connectivity, which have a high spatio-temporal variability in ephemeral rivers. The water connectivity of the whole river system is temporally variable. It only takes place in a scarce number of rainfall events. This temporal variability affects the sediment connectivity, which already has a significant spatial variability, because it depends on the longitudinal, lateral and vertical connectivity of the different system elements (Fryers, 2013). These hydro-sedimentary disconnections facilitate vegetation encroachment processes (such as the period 2004-2012 in the Palancia River), fixing sediments and limiting channel sediment removal to the highest flood events. A lack of water and sediment connectivity has been also observed in this river in the unequal spatial recovery detected in 1988 (between confined/higher and unconfined/lower sectors).

The third restriction is channel incision. It is a direct consequence of the abovementioned processes, and also acts as an additional restriction factor for channel recovery. Incision causes lateral microterrace formation, which in turn stimulates vegetation encroachment processes and obstructs lateral channel migration. We have observed how the wide and slightly-incised sectors (b and d) show the highest variability in the MRI and achieve the highest MRI values after floods, while the sectors that are severely incised (e and f) have more intense narrowing processes, reducing the space for channel mobility. This effect, caused by the hydraulic confinement of floods in a deeper section, hinders their morphological recovery processes.

Finally, in-stream human activities, such as maintenance or clearing works, have also been a restriction factor in this case. We have observed the severe impact of these actions in the variation of the MRI in sector *e* and more markedly in sector *f*, which have never recovered the morphological diversity that they had in 1946. River systems follow adjustment trajectories (Dufour and Piegay, 2009), which are particularly complex in ephemeral channels. Interrupting these trajectories, without a complete understanding of the sedimentary balance of the river, is counter-productive. Before designing any restoration or recovery intervention, it is necessary to analyze and understand recent river trajectories (Brierley and Fryers, 2005; Brierley et al., 2008; Surian et al., 2009; Scorpio et al., 2016). In this particular case, most of the changes that affected the river basin and channel contributed to increase sediment deficit conditions. For this reason, conducting operations such as river bed flattering and compaction slow down adjustment processes and prevent the river from attaining a new stage of equilibrium.

In this work, ~~we have seen the~~ ~~enormous capacity of~~ ephemeral rivers to regenerate their morphology through recurrent floods. The events of 1988-1989-1990 and the flood of 2000 partially reconstructed the original wandering pattern in some areas of the river. Due to these processes, and considering the current river adjustment trajectory, new “maintenance” or clearing actions are not recommended in rivers under these conditions. These operations should be avoided in the river corridor. The best intervention is not to intervene, and to let the rivers complete their adjustment processes according to their current sedimentary context.

CONCLUSIONS

The convergence of indirect (land use changes) and direct changes (gravel extraction, channelization and flood events) have affected the recovery of the Palancia River channel forms after the devastation caused by intensive instream mining. The river channel has adjusted to new sediment conditions by narrowing, increasing incision and shifting from predominant wandering forms to a single channel or slightly wandering pattern.

The spatial variability of these changes has been assessed through a cross-analysis of several drivers. The river corridor width and initial confinement are important drivers determining rivers ability to respond to these changes. The expected trend was that wide sectors could recover the high morphological diversity that they had before gravel mining devastation, however, incision and river clearing works have altered this behavior.

Incision has played a major role in the distribution and intensity of the process of recovery, interacting with gravel channel narrowing and vegetation encroachment. It has caused the confinement of the gravel channel in the lower reach, limiting the scope of the morphological recovery process to a narrow corridor. Together with incision, the alternation of wet and dry periods is also critical to the recovery of the original forms of the Palancia River. The diversity of river forms increases immediately after flood events, whereas vegetation colonization is directly linked to the absence of floods, up to the point of complete occupation of the river corridor in some wide and slightly incised areas.

This case study shows the capacity of ephemeral rivers to spontaneously readapt their channel forms to changing watershed and local conditions without any additional human intervention. The channelization works developed in the 1990s, and the clearing and channelization project executed in 2009 only served to hinder this natural readjustment process, significantly reducing morphological diversity. The Palancia River case highlights the necessity of achieving a complete understanding of basin and river channel trajectories prior to the design of any maintenance or restoration operations. It also should lead to reconsideration of those investments in ephemeral river restoration which are likely to alter the auto-recovery processes.

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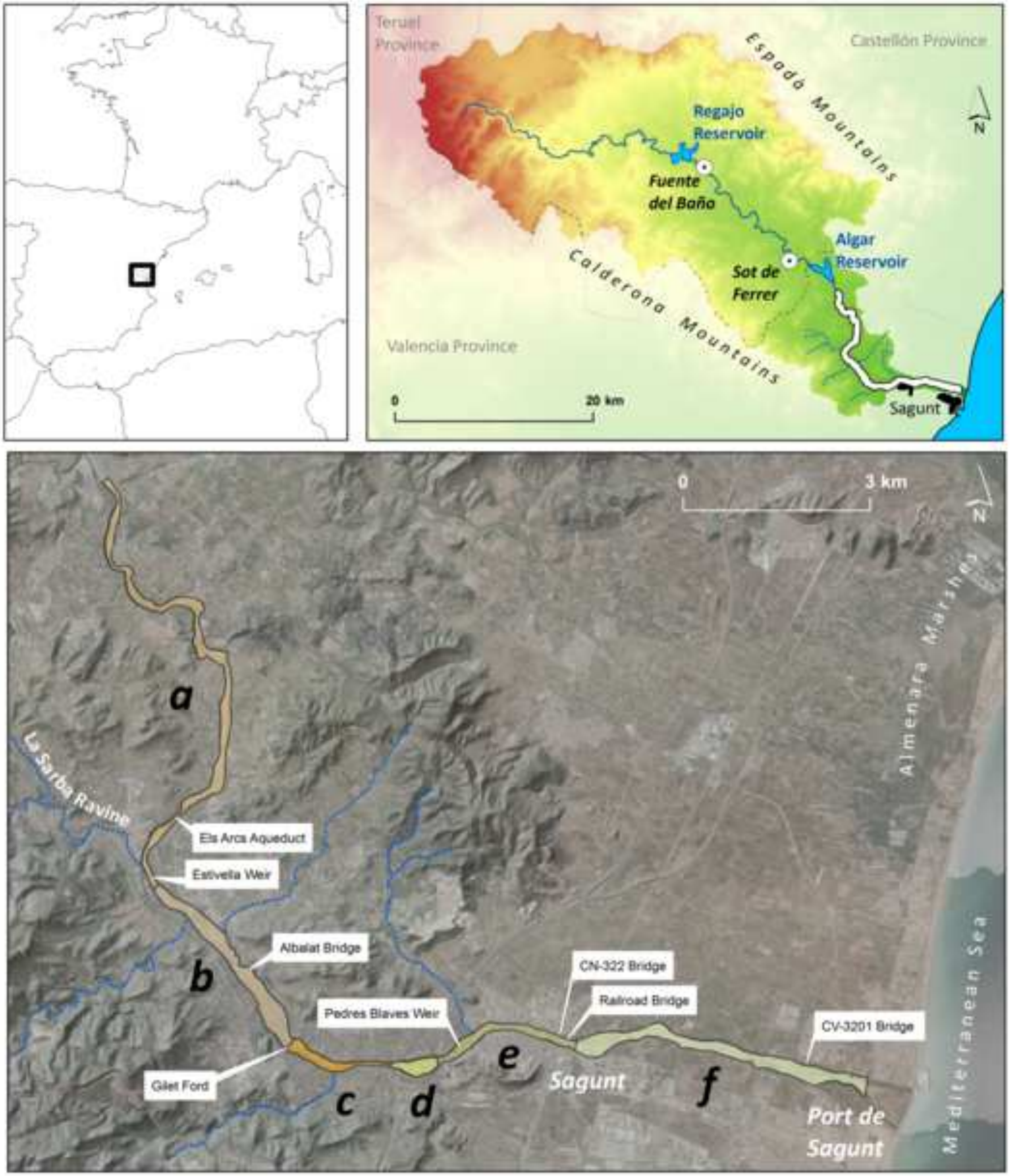
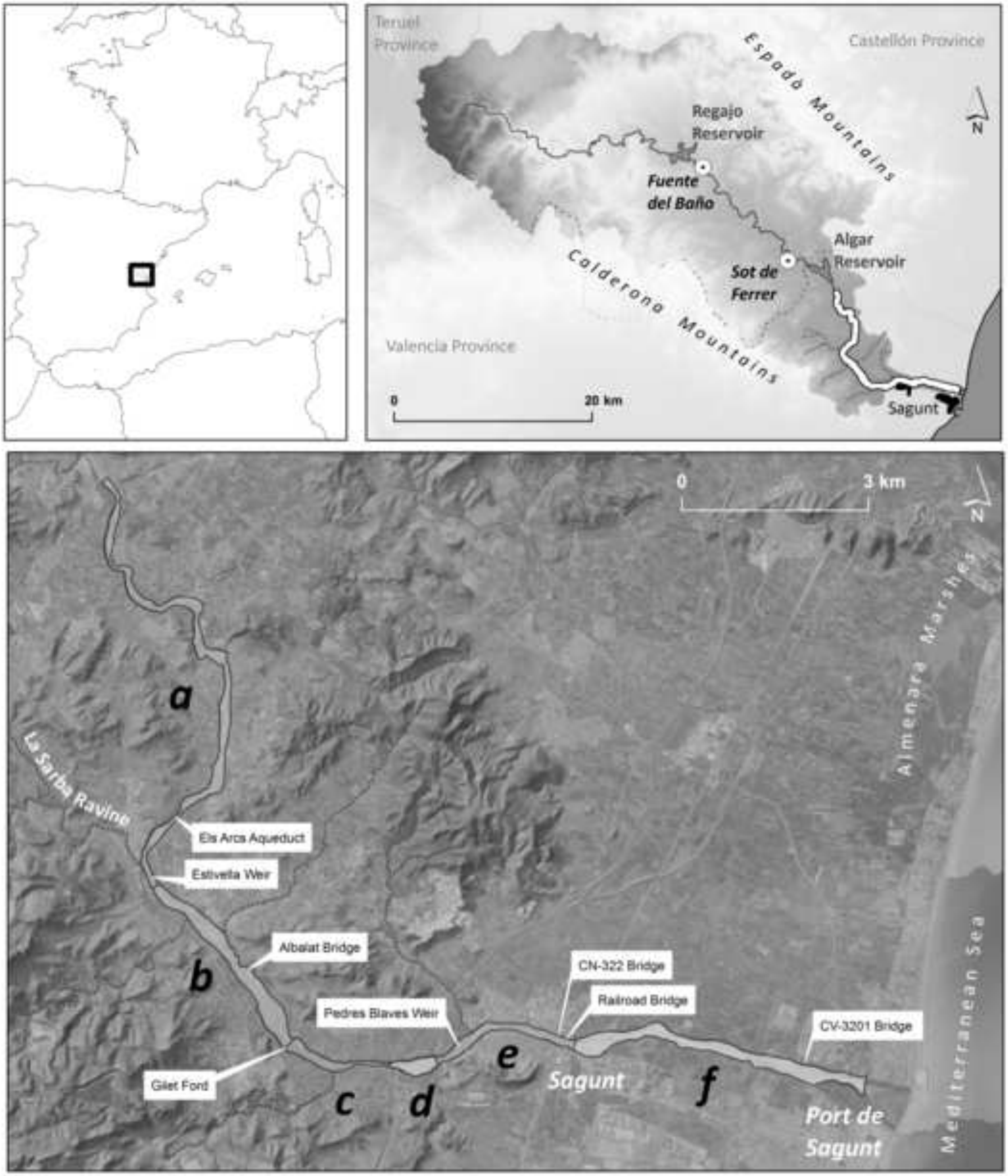

Teruel Province
Castellón Province
Espadà Mountains
Regajo Reservoir
Fuente del Baño
Algar Reservoir
Sot de Ferrer
Calderona Mountains
Valencia Province
0
20 km
N
Sagunt
0
3 km
N
Almenara Marshes
La Sarba Ravine
a
Els Arcs Aqueduct
Estivella Weir
Albalat Bridge
b
Gilet Ford
c
Pedres Blaves Weir
d
e
CN-322 Bridge
Railroad Bridge
Sagunt
f
CV-3201 Bridge
Port de Sagunt
Mediterranean Sea


Teruel Province
Castellón Province
Espadà Mountains
Regajo Reservoir
N
Fuente del Baño
Algar Reservoir
Sot de Ferrer
Calderona Mountains
Valencia Province
0
20 km
Sagunt
0
3 km
N
Almenara Marshes
a
La Sarba Ravine
Els Arcs Aqueduct
Estivella Weir
Albalat Bridge
b
CN-322 Bridge
Railroad Bridge
Pedres Blaves Weir
CV-3201 Bridge
Mediterranean Sea
e
Sagunt
f
Gilet Ford
c
d
Port de Sagunt

Figure

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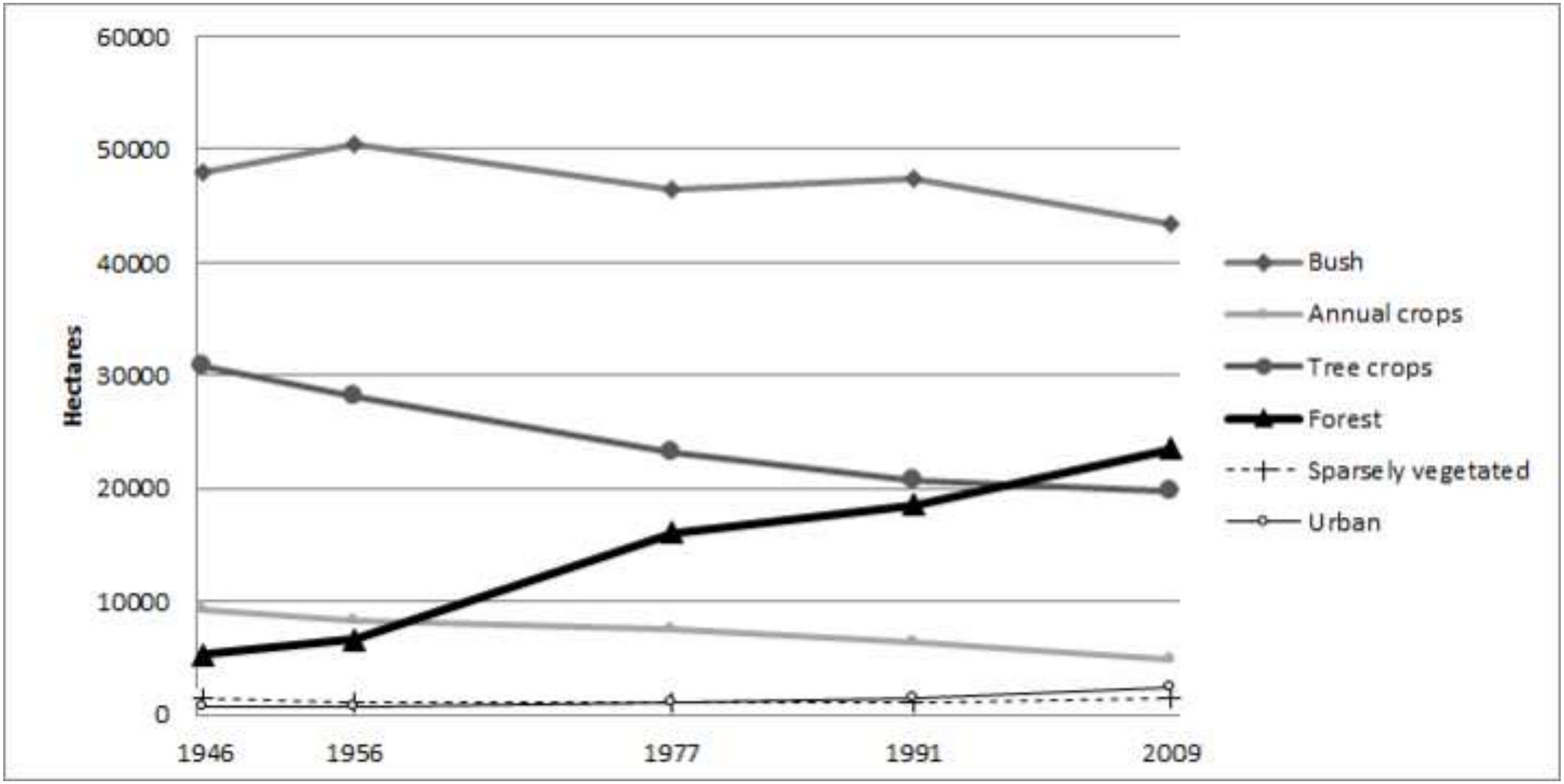
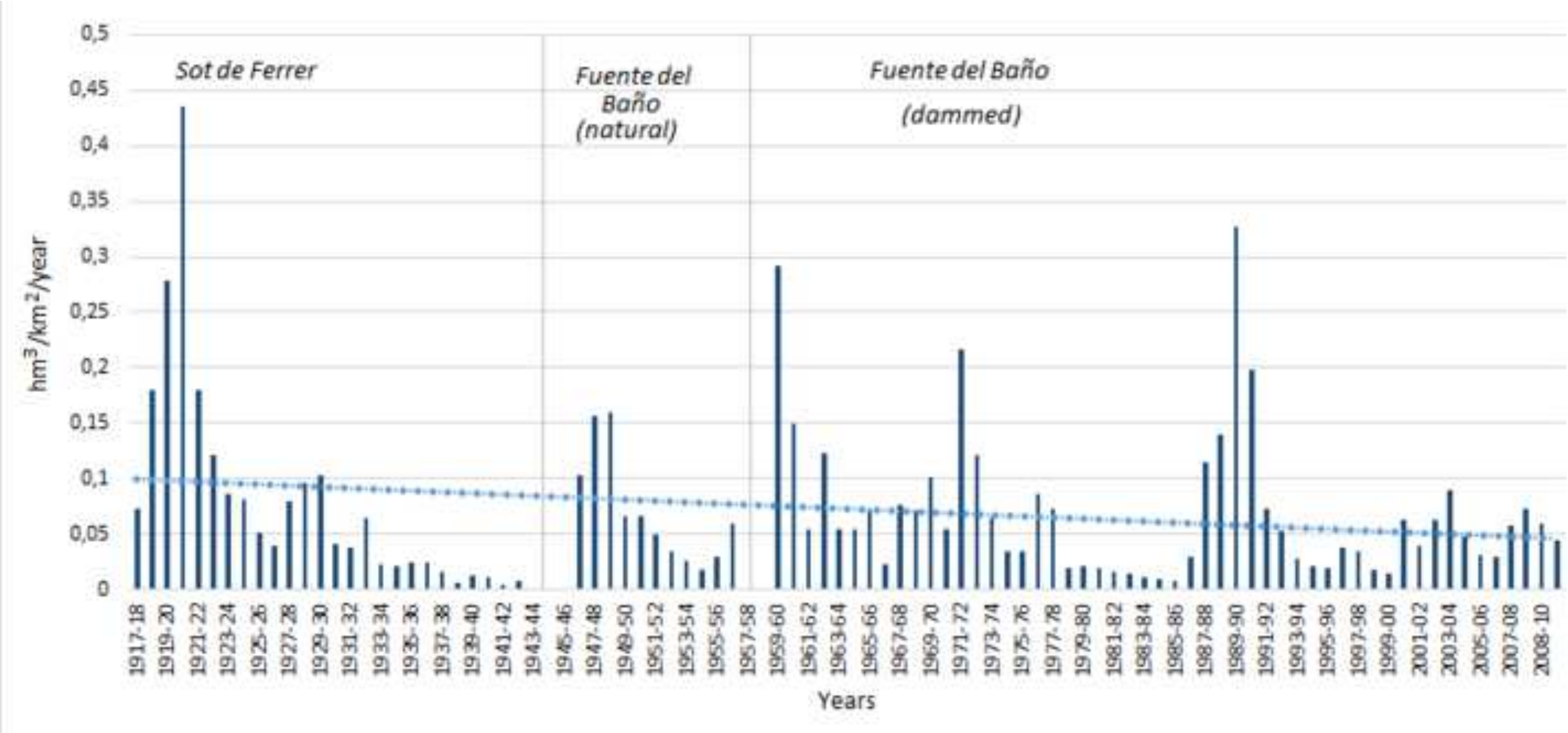


Figure 3


Sot de Ferrer
Fuente del Baño (natural)
Fuente del Baño (dammed)
hm³/km²/year
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
1917-18
1919-20
1921-22
1923-24
1925-26
1927-28
1929-30
1931-32
1933-34
1935-36
1937-38
1939-40
1941-42
1943-44
1945-46
1947-48
1949-50
1951-52
1953-54
1955-56
1957-58
1959-60
1961-62
1963-64
1965-66
1967-68
1969-70
1971-72
1973-74
1975-76
1977-78
1979-80
1981-82
1983-84
1985-86
1987-88
1989-90
1991-92
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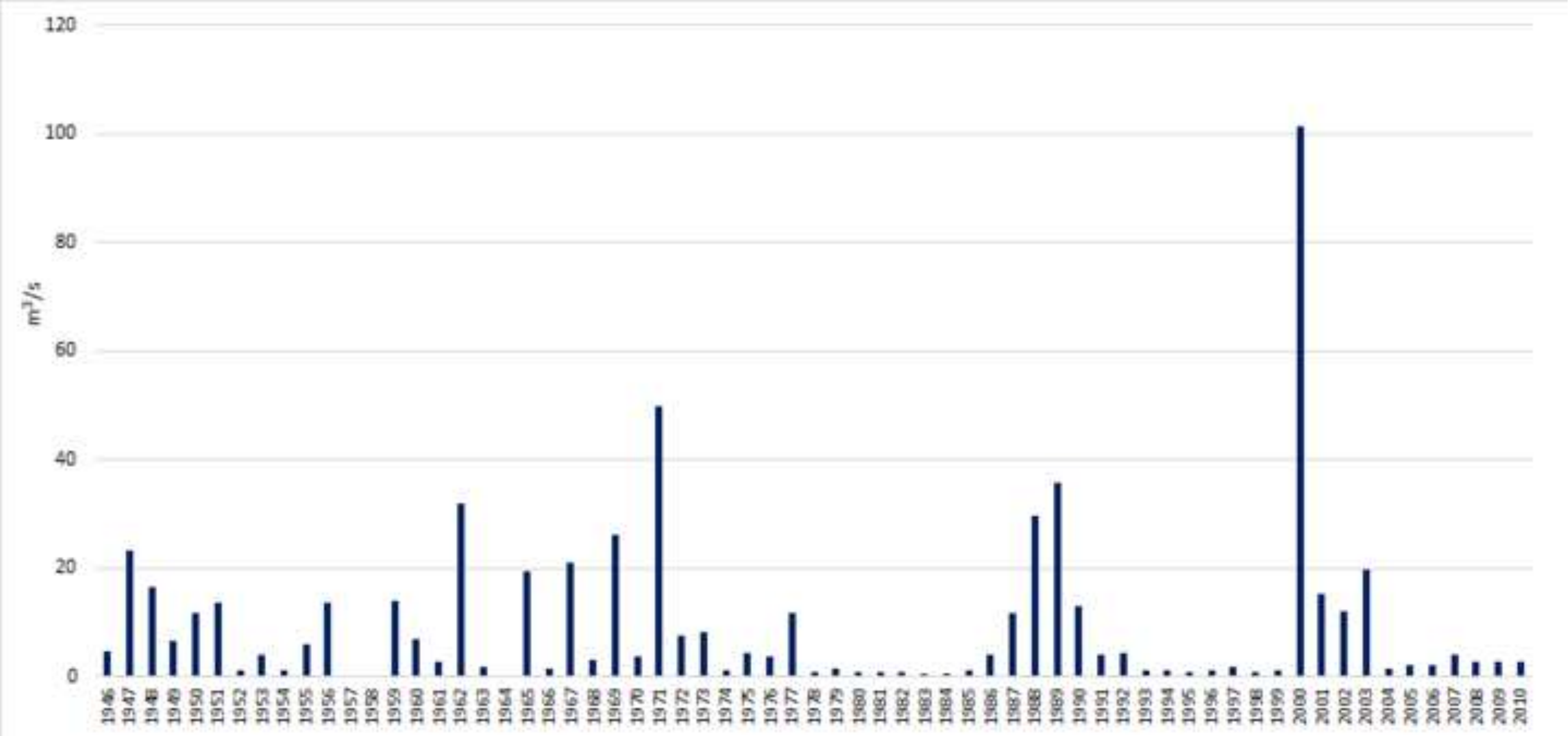
1997-98
1999-00
2001-02
2003-04
2005-06
2007-08
2008-10
Years

Figure 4


120
100
80
60
40
20
0
m^3/s
1946
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1948
1949
1950
1951
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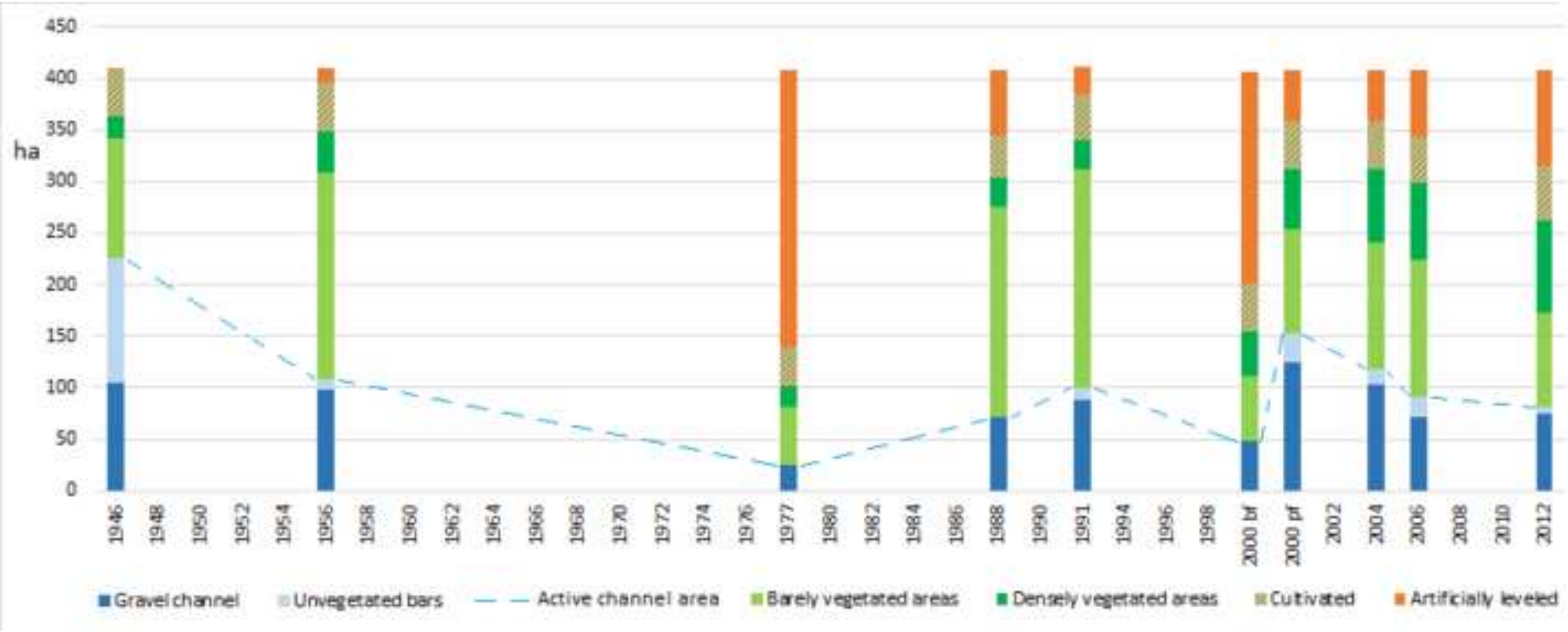
Figure 5


ha
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100
150
200
250
300
350
400
450
1946
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1964
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1982
1984
1986
1988
1990
1991
1994
1996
1998
2000 bf
2000 pf
2002
2004
2006
2008
2010
2012
Gravel channel
Unvegetated bars
Active channel area
Barely vegetated areas
Densely vegetated areas
Cultivated
Artificially leveled

Figure 5 black and white

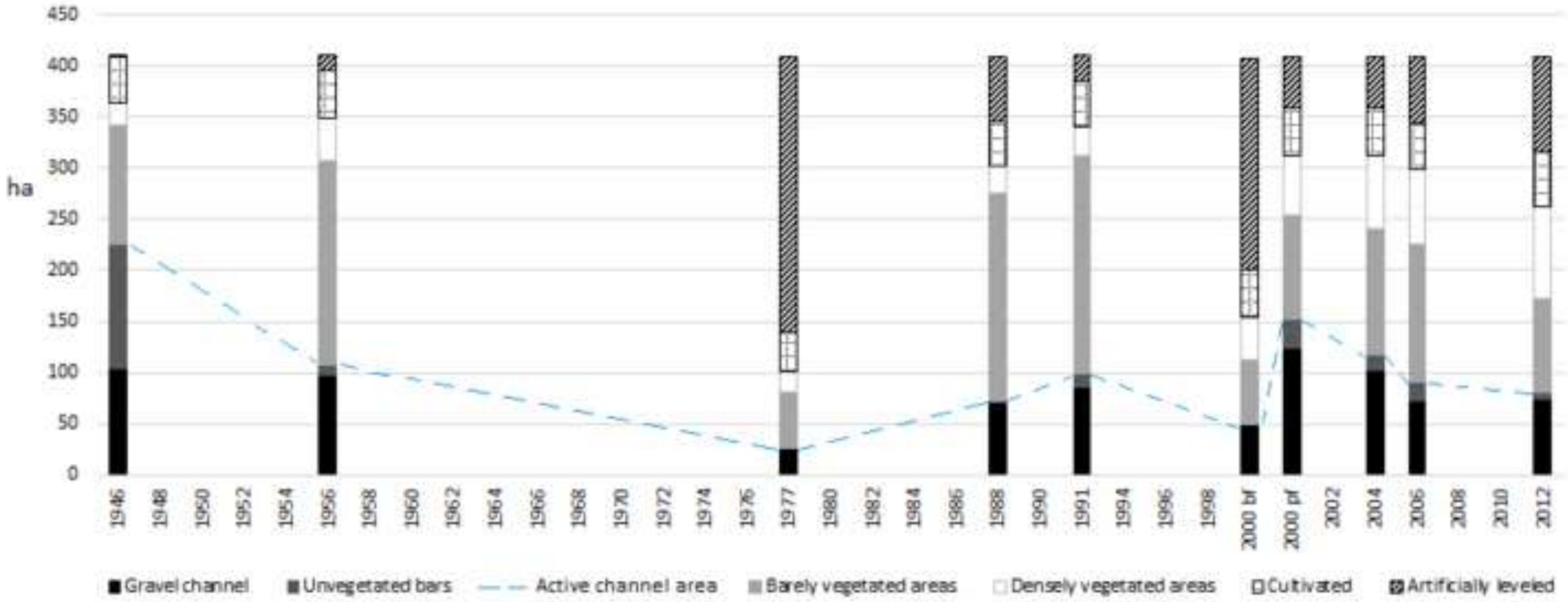
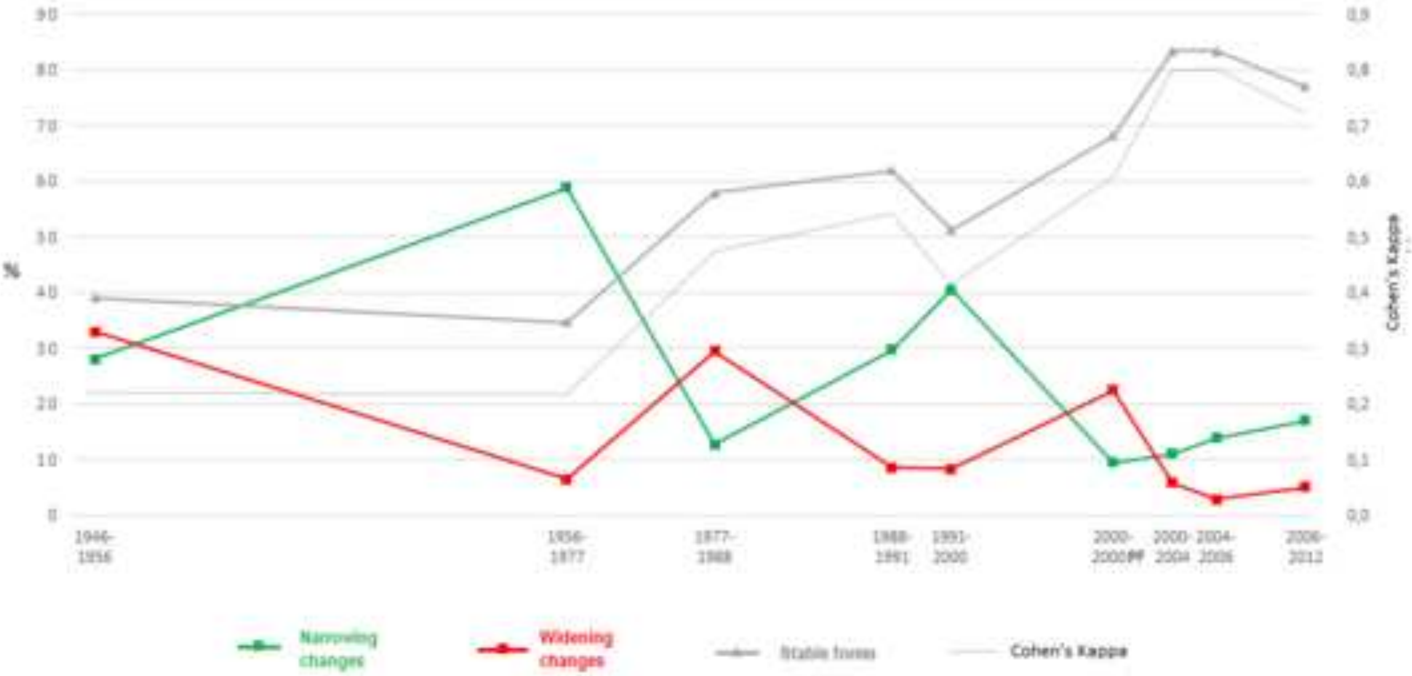
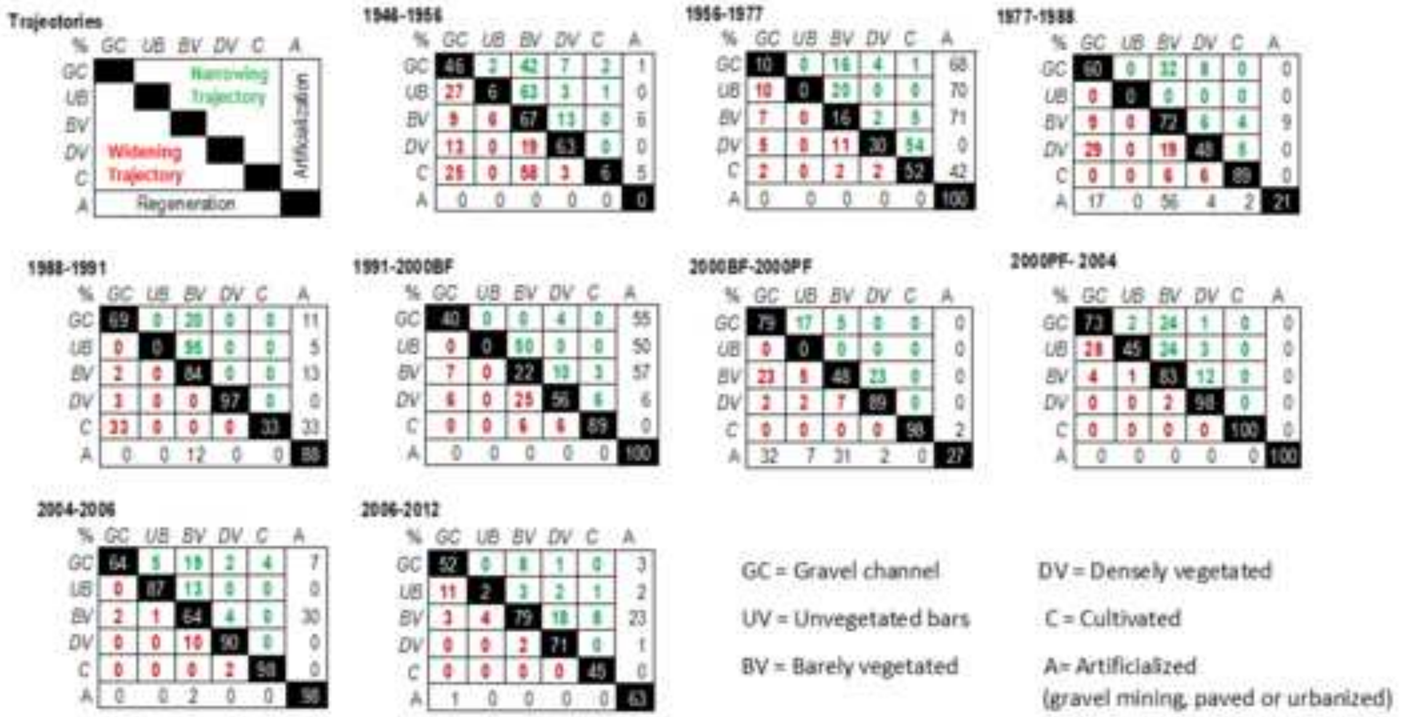


Figure 6





1946-1956

%	GC	UB	BV	DV	C	A
GC	46	2	42	7	2	1
UB	27	6	63	3	1	0
BV	9	6	67	13	0	6
DV	13	0	19	63	0	0
C	25	0	58	3	6	5
A	0	0	0	0	0	0

1956-1977

%	GC	UB	BV	DV	C	A
GC	10	0	16	4	1	68
UB	10	0	20	0	0	70
BV	7	0	16	2	5	71
DV	5	0	11	30	54	0
C	2	0	2	2	52	42
A	0	0	0	0	0	100

1977-1988

%	GC	UB	BV	DV	C	A
GC	60	0	32	8	0	0
UB	0	0	0	0	0	0
BV	9	0	72	6	4	9
DV	29	0	19	48	5	0
C	0	0	6	6	89	0
A	17	0	56	4	2	21

1988-1991

%	GC	UB	BV	DV	C	A
GC	69	0	20	0	0	11
UB	0	0	95	0	0	5
BV	2	0	84	0	0	13
DV	3	0	0	97	0	0
C	33	0	0	0	33	33
A	0	0	12	0	0	88

1991-2000BF

%	GC	UB	BV	DV	C	A
GC	40	0	0	4	0	55
UB	0	0	50	0	0	50
BV	7	0	22	10	3	57
DV	6	0	25	56	6	6
C	0	0	6	6	89	0
A	0	0	0	0	0	100

2000BF-2000PF

%	GC	UB	BV	DV	C	A
GC	79	17	5	0	0	0
UB	0	0	0	0	0	0
BV	23	5	48	23	0	0
DV	2	2	7	89	0	0
C	0	0	0	0	98	2
A	32	7	31	2	0	27

2000PF- 2004

%	GC	UB	BV	DV	C	A
GC	73	2	24	1	0	0
UB	28	45	24	3	0	0
BV	4	1	83	12	0	0
DV	0	0	2	98	0	0
C	0	0	0	0	100	0
A	0	0	0	0	0	100

2004-2006

%	GC	UB	BV	DV	C	A
GC	64	5	19	2	4	7
UB	0	87	13	0	0	0
BV	2	1	64	4	0	30
DV	0	0	10	90	0	0
C	0	0	0	2	98	0
A	0	0	2	0	0	98

2006-2012

%	GC	UB	BV	DV	C	A
GC	52	0	8	1	0	3
UB	11	2	3	2	1	2
BV	3	4	79	10	8	23
DV	0	0	2	71	0	1
C	0	0	0	0	45	0
A	1	0	0	0	0	63

GC = Gravel channel
UV = Unvegetated bars
BV = Barely vegetated
DV = Densely vegetated
C = Cultivated
A= Artificialized
(gravel mining, paved or urbanized)

Figure 6 black and white

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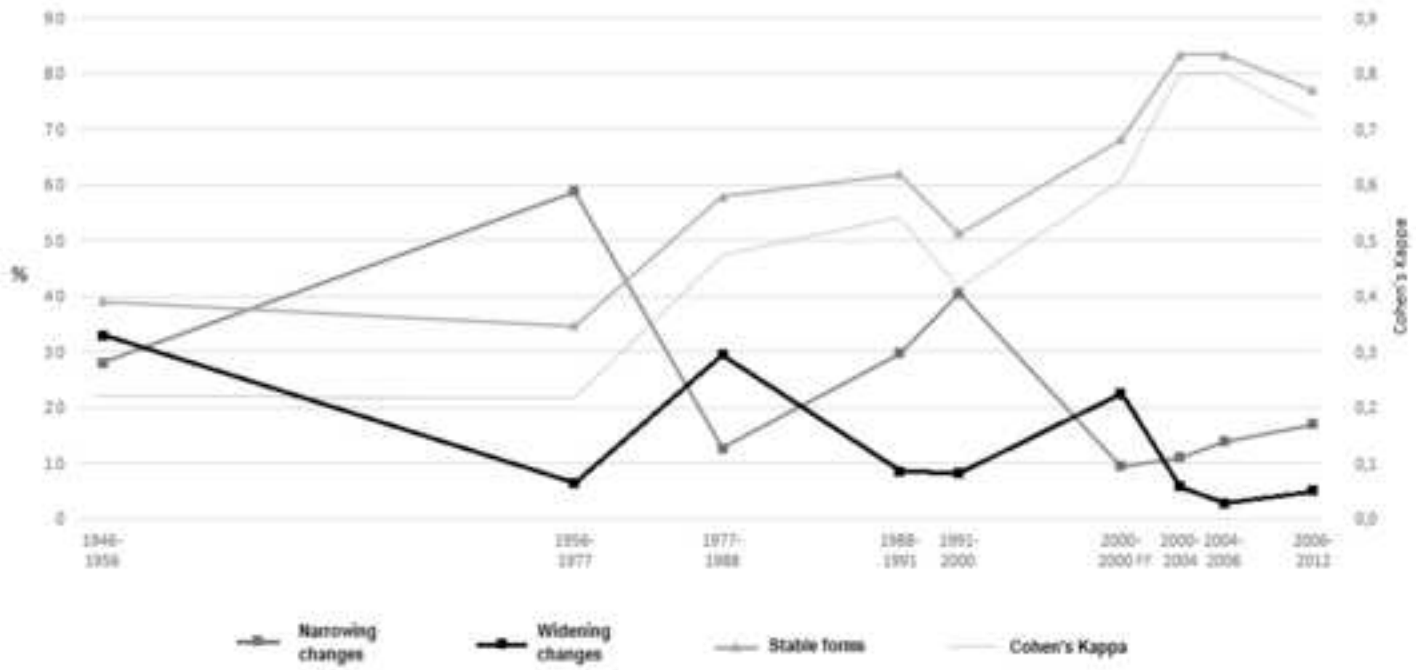
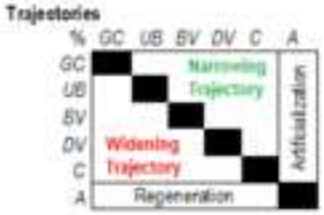


Trajectories



1946-1956

%	GC	UB	BV	DV	C	A
GC	46	2	42	7	2	1
UB	27	6	63	3	1	0
BV	9	6	67	13	0	6
DV	13	0	19	63	0	0
C	25	0	58	3	6	5
A	0	0	0	0	0	0

1956-1977

%	GC	UB	BV	DV	C	A
GC	10	0	16	4	1	68
UB	10	0	20	0	0	70
BV	7	0	16	2	5	71
DV	5	0	11	30	54	0
C	2	0	2	2	52	42
A	0	0	0	0	0	100

1977-1988

%	GC	UB	BV	DV	C	A
GC	60	0	32	8	0	0
UB	0	0	0	0	0	0
BV	9	0	72	6	4	9
DV	29	0	19	48	5	0
C	0	0	6	6	89	0
A	17	0	56	4	2	21

1988-1991

%	GC	UB	BV	DV	C	A
GC	69	0	20	0	0	11
UB	0	0	95	0	0	5
BV	2	0	84	0	0	13
DV	3	0	0	97	0	0
C	33	0	0	0	33	33
A	0	0	12	0	0	88

1991-2000BF

%	GC	UB	BV	DV	C	A
GC	40	0	0	4	0	55
UB	0	0	50	0	0	50
BV	7	0	22	10	3	57
DV	6	0	25	56	6	6
C	0	0	6	6	89	0
A	0	0	0	0	0	100

2000BF-2000PF

%	GC	UB	BV	DV	C	A
GC	79	17	5	0	0	0
UB	0	0	0	0	0	0
BV	23	5	48	23	0	0
DV	2	2	7	89	0	0
C	0	0	0	0	98	2
A	32	7	31	2	0	27

2000PF- 2004

%	GC	UB	BV	DV	C	A
GC	73	2	24	1	0	0
UB	28	45	24	3	0	0
BV	4	1	83	12	0	0
DV	0	0	2	98	0	0
C	0	0	0	0	100	0
A	0	0	0	0	0	100

2004-2006

%	GC	UB	BV	DV	C	A
GC	64	5	19	2	4	7
UB	0	87	13	0	0	0
BV	2	1	64	4	0	30
DV	0	0	10	90	0	0
C	0	0	0	2	98	0
A	0	0	2	0	0	98

2006-2012

%	GC	UB	BV	DV	C	A
GC	52	0	8	1	0	3
UB	11	2	3	2	1	2
BV	3	4	79	18	8	23
DV	0	0	2	71	0	1
C	0	0	0	0	45	0
A	1	0	0	0	0	63

GC = Gravel channel
UV = Unvegetated bars
BV = Barely vegetated
DV = Densely vegetated
C = Cultivated
A= Artificialized
(gravel mining, paved or urbanized)

Figure 7

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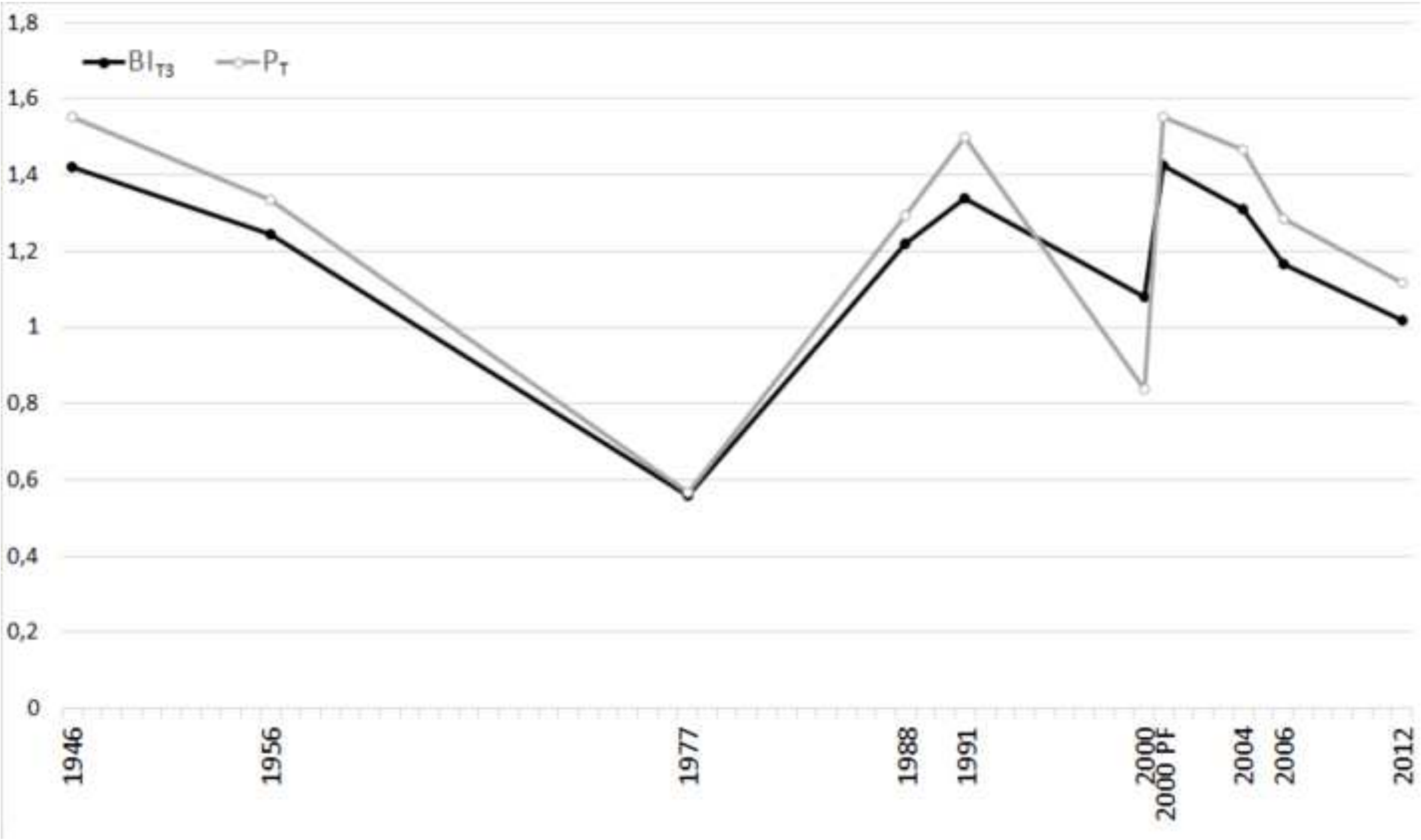
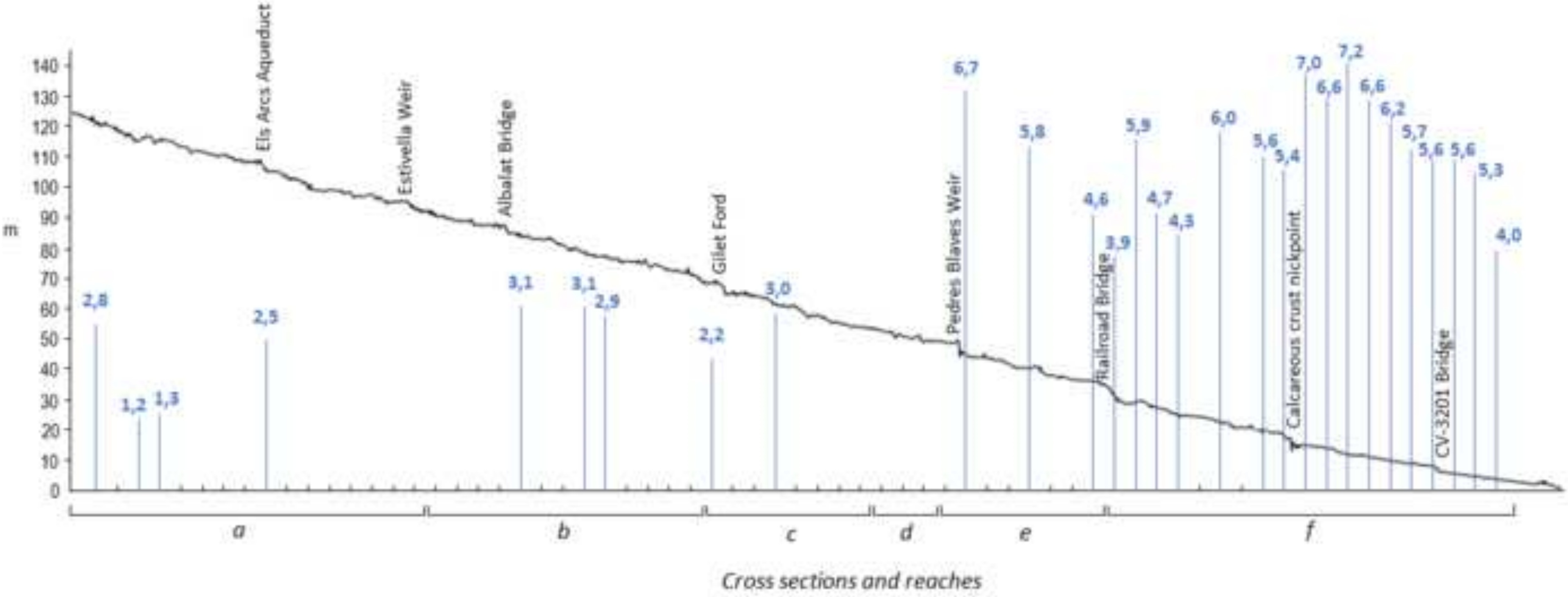


Figure 8


m
140
130
120
110
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Els Arcs Aqueduct
Estivella Weir
Albalat Bridge
Gilet Ford
Pedres Blaves Weir
Railroad Bridge
Calcareous crust nickpoint
CV-3201 Bridge
2,8
1,2
1,3
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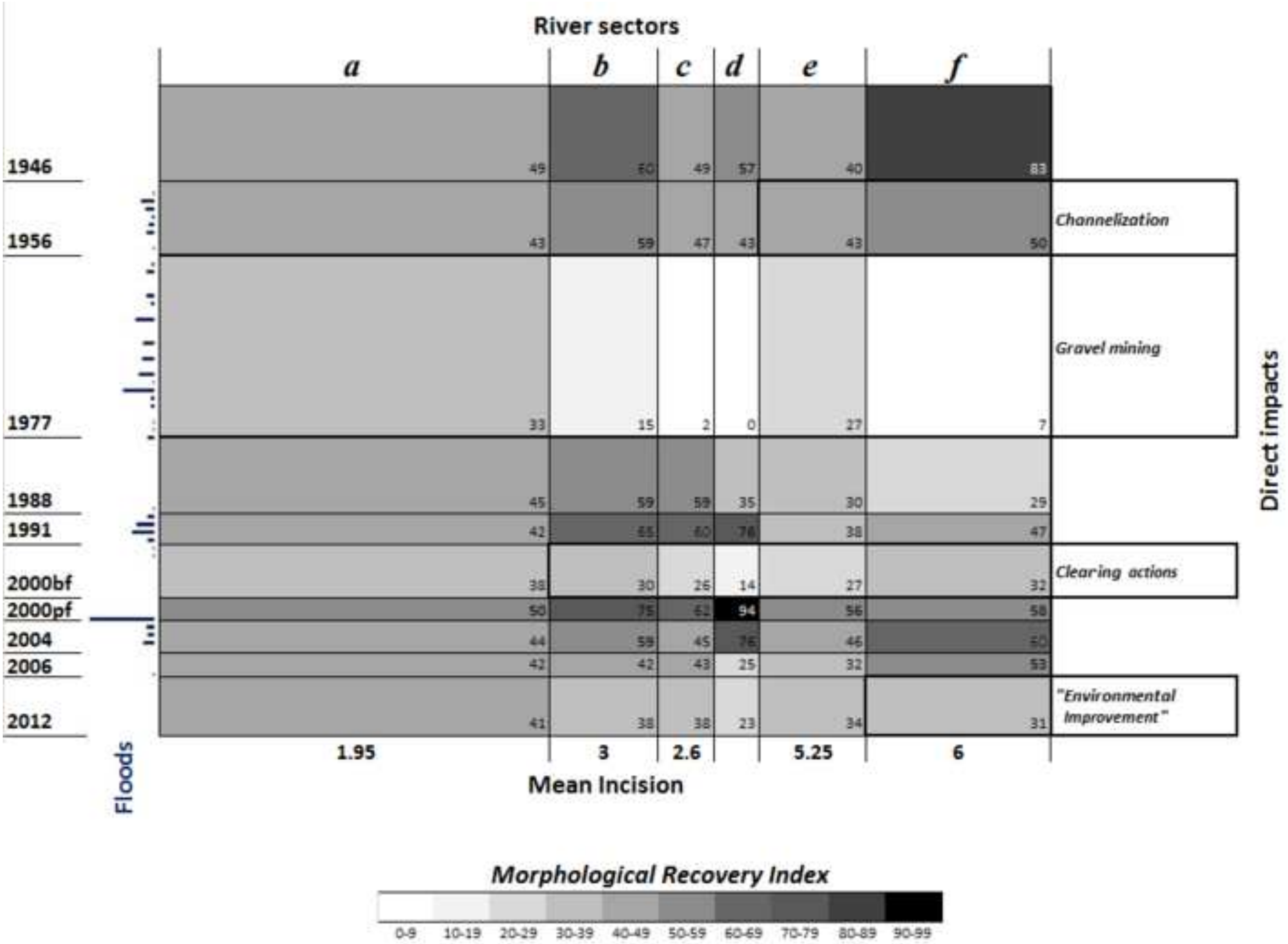
6,0
5,6
5,4
7,0
6,6
7,2
6,6
6,2
5,7
5,6
5,6
5,3
4,0
a
b
c
d
e
f
Cross sections and reaches

Figure 9 black and white



	a	b	c	d	e	f
1946	49	60	49	57	40	83
1956	43	59	47	43	43	50
1977	33	15	2	0	27	7
1988	45	59	59	35	30	29
1991	42	65	60	76	38	47
2000bf	38	30	26	14	27	32
2000pf	50	75	62	94	56	58
2004	44	59	45	76	46	60
2006	42	42	43	25	32	53
2012	41	38	38	23	34	31
Mean Incision	1.95	3	2.6		5.25	6

Figure 9

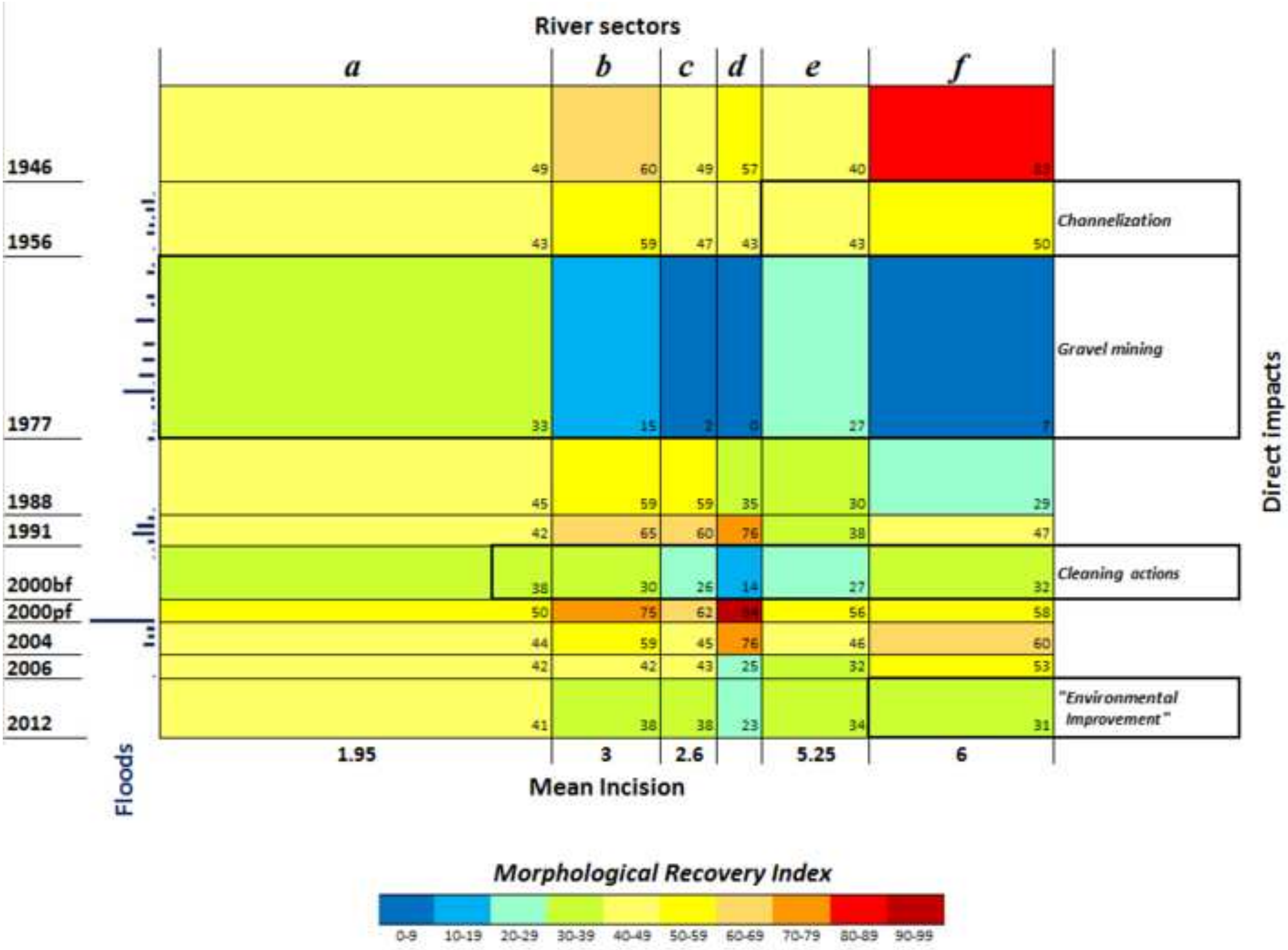

River sectors
a
b
c
d
e
f
1946
49
60
49
57
40
83
1956
43
59
47
43
43
50
Channelization
1977
33
15
2
0
27
7
Gravel mining
1988
45
59
59
35
30
29
1991
42
65
60
76
38
47
2000bf
38
30
26
14
27
32
Cleaning actions
2000pf
50
75
62
94
56
58
2004
44
59
45
76
46
60
2006
42
42
43
25
32
53
2012
41
38
38
23
34
31
"Environmental Improvement"
Direct impacts
Floods
1.95
3
2.6
5.25
6
Mean Incision
Morphological Recovery Index
0-9
10-19
20-29
30-39
40-49
50-59
60-69
70-79
80-89
90-99

Figure 10

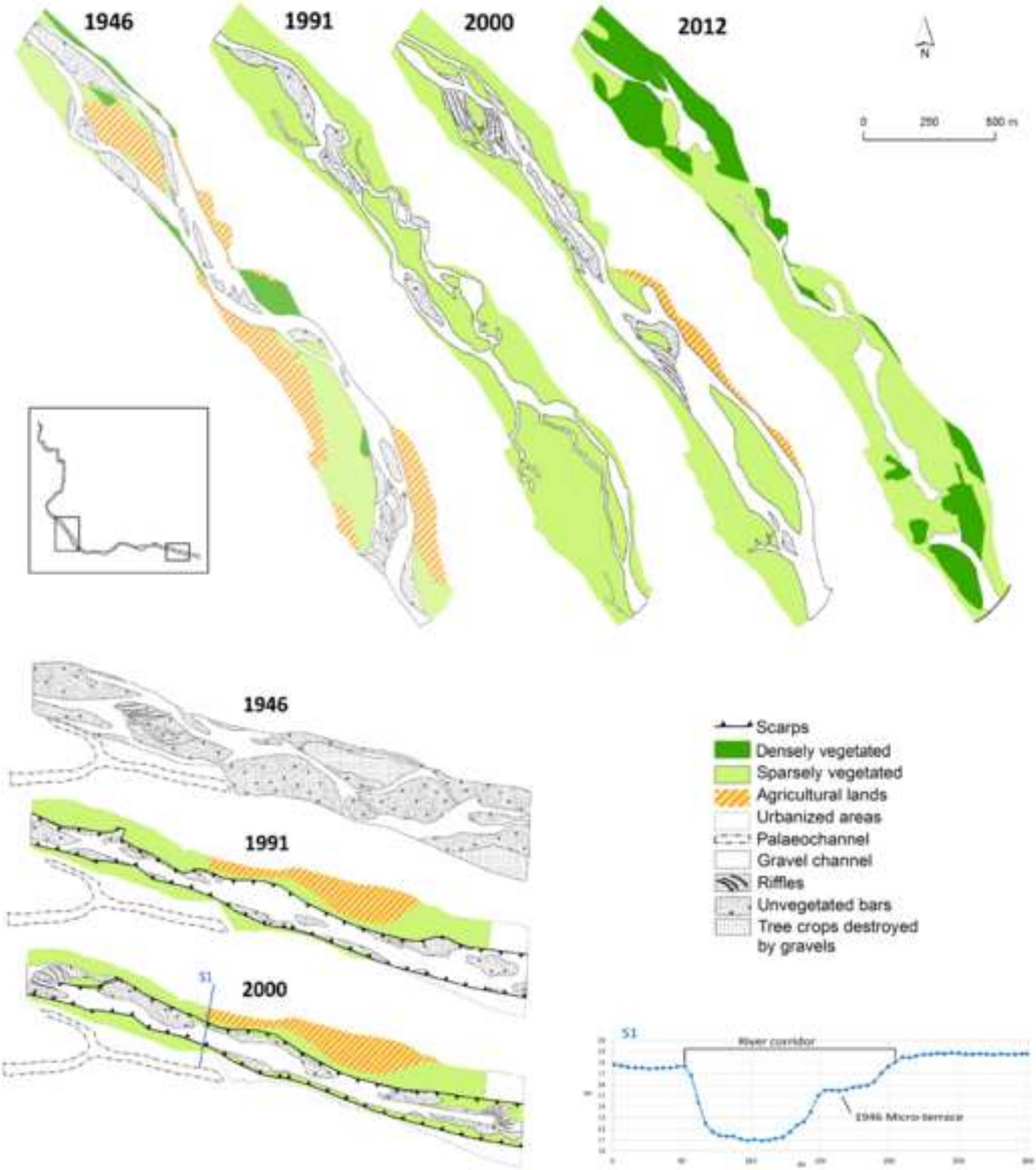

1946
1991
2000
2012
N
0
250
500 m
1946
1991
2000
S1
Scarps
Densely vegetated
Sparsely vegetated
Agricultural lands
Urbanized areas
Palaeochannel
Gravel channel
Riffles
Unvegetated bars
Tree crops destroyed by gravels
S1
River corridor
1946 Micro-terrace

Figure 10 black and white

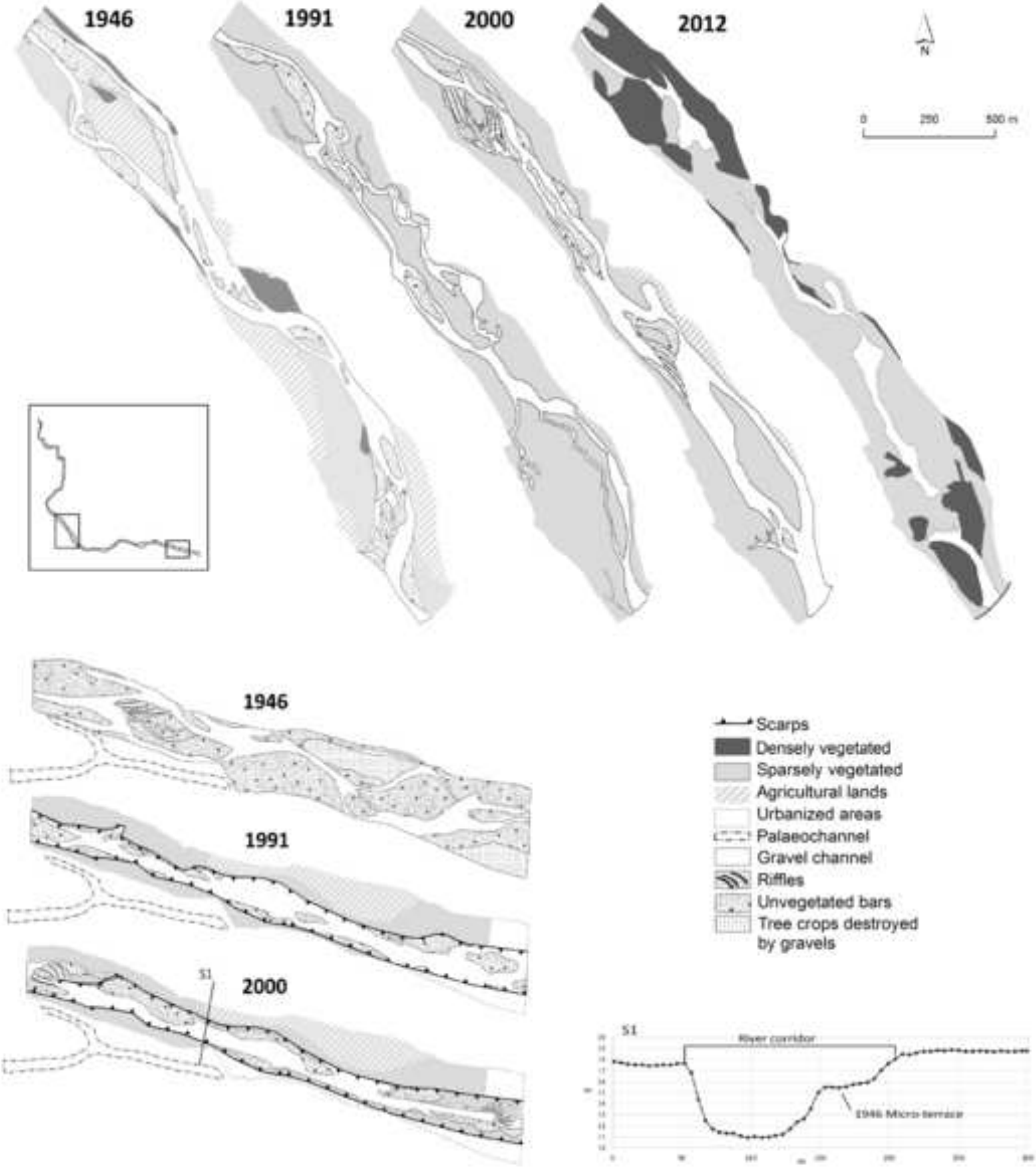


Figure Captions

Figure 1. Palancia river basin. Study area and gauging stations. Sketch of location of the study area and the six river reaches considered for spatial analysis.

Figure 2. Land use changes in the Palancia River basin between 1946 and 2009.

Figure 3. Annual unit discharge in series prior and subsequent to Regajo Reservoir construction.

Figure 4. Major flood events. Daily maximum flow between 1946 and 2010.

Figure 5. Channel forms areas and AC area (line). BF for “before flood” and PF for “post-flood”.

Figure 6. River prevailing trajectories. The black diagonal show the stable forms. Triangle on the left for widening trajectory changes. Triangle on the right for narrowing trajectory changes. Margins for artificialization or regeneration changes percentages. Above graphic summarizes the trends, providing a characterization of the predominant trajectories in each period.

Figure ~~7~~. Longitudinal section of the Palancia River, showing incision between 1946 and 2009 calculated in various river cross-sections.

Figure ~~8~~. Changes in the total sinuosity index (P_T) and the channel count index ($B_I T_I$). BF for “before flood” and PF for “post-flood”.

Figure 9. Morphological Recovery Index distribution along all the river reaches ~~and~~ the study period. Main drivers explaining spatial variability (floods, human direct impacts, river corridor width and incision) are also included to achieve a complete vision of the complex interaction among processes and forms.

Figure 10. Morphological changes in two reaches. Above, wide reach between the Albalat Bridge and the Gilet Ford, where flow energy dissipates. It had a clear wandering pattern in 1946. Gravel mining severely altered river forms and when, after some minor floods, the river reconstructed its forms (1991), created narrow and highly sinuous channels, due to the numerous gravel pits and dumps. The October 2000 flood had energy enough to completely reconstruct the wandering pattern, but the subsequent lack of floods has facilitated intense vegetation encroachment. Below, a reach in the unconfined sector. Incision (see cross section) created a longitudinal scarp that facilitated flow concentration and channel narrowing, also stimulating vegetation encroachment during the last decade. Cross section also shows the 1946 micro-terrace level.