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Assessment of channel changes in a Mediterranean ephemeral stream since the early 20th century. The Rambla de Cervera, Eastern Spain.

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Abstract

An analysis of morphological changes during the last six decades is presented for a 16.5 km reach of the Rambla de Cervera, a Mediterranean ephemeral stream located in Eastern Spain. Channel changes were analysed through a range of techniques, specifically the analysis of aerial photographs with geographical information systems (GIS) and comparison of topographic surveys. The gravel channel underwent a general decline over the study period, losing width (68.5%) and surface area (45.7%) due to the development of established islands frequently attached to the floodplain. These morphological changes exhibit an interesting temporal variability, with a maximum decrease of the gravel channel in the period 1946-1956 and another narrowing stage between 1977-1991. There were also two periods (1956-1977 and 1991-2006) of mixed performance. In addition, incision processes occurred along the entire study reach at an average depth of 3.5 m. Natural and human-induced factors producing contradictory effects are considered responsible for changes in the Rambla de Cervera.

Key words: Channel changes, island dynamics, land use changes, gravel mining, channel incision, channel narrowing.

1. Introduction

Over the last two centuries, Mediterranean rivers have undergone complex adjustments. Flow and sediment supply have both fluctuated through time, meaning that continuous adjustment have taken place through the erosion and deposition of sediment. Climatic changes and human activities have been associated to these adjustments influencing channel discharge and sediment supply. Much discussion has focused on the effects of human activities and its relative importance compared with climatic impacts in fluvial systems and several studies have analyzed the links between morphological changes and anthropogenic activity in the region (Hooke, 2006; Gurnell et al., 2009). In these works, channel narrowing and channel incision occurring throughout the 20th century have been interpreted as adjustments to the new environmental conditions.

The decrease in flow discharge and sediment load (Garófano-Gómez et al., 2012; González et al., 2010; Cadol et al., 2011; Liébault and Piégay, 2001; Pont, et al., 2009) have been considered as the main causes of narrowing and incision in the Mediterranean rivers. These alterations of river basin conditions have been frequently caused by anthropogenic actions such as dam construction, reforestation, torrent control works or river channelization (Roux et al., 1989; Bravard et al. 1997; Rinaldi, 2003; Surian and Rinaldi, 2003; Surian and Cissotto, 2007; García-Ruiz and Lana-Renault, 2011). Gravel extraction has also had a profound impact on rivers in the region (Surian and Rinaldi, 2003; Surian et al., 2009; Rinaldi et al. 2005; Liébault and Piégay, 2002; Wishart et al., 2008), mainly upstream-and downstream-progressing river incision, lateral channel instability and bed armouring. The resultant incision alters the frequency of floodplain inundation along the river courses, lowers valley floor water tables and frequently leads to the destruction of bridges and channelization structures (Rovira et al. 2005; Batalla, 2003).

The observed changes in channel morphology are also linked to changes in river vegetation encroachment. The relation between plants and physical processes affect conditions for island and floodplain evolution. Vegetation traps and stabilises sediments, organic matter and the propagules, and they modify the local sedimentary and morphological environment by driving the development of landforms. Consequently, channel narrowing is frequently associated with vegetation development. The role of vegetation as a trigger for planform change and recovery is not yet well known, but it seems to be essential in river changes induced by human action (Gurnell et al., 2009). Linkages between the colonisation of vegetation and river morphology and morphodynamics of humid gravel-bed rivers have been recently established (Zanoni et al., 2008; Tal and Paola, 2007; Wyrick and Klingeman, 2011; Bertoldi et al. 2011; Gurnell et al., 2012). The interaction between vegetation and fluvial processes in ephemeral rivers has received relatively less attention. Recent works have shown that the influence of vegetation on river changes is strongly dependent to the variations on the temporal sequence of flood events (Hooke and Mant, 2002; Sandercock et al. 2007).

In the Mediterranean region of Europe, researchers have attempted to establish a chronology of recent historical changes in river morphology, linked to human actions and climatic changes. In French rivers, channel narrowing in the first half of the 20th century has been associated with decreased discharges and sediment supply at the end of the Little Ice Age. In contrast, channel reduction in the second half of the 20th century is considered a human-induced fluvial adjustment (Bravard, et al. 1997; Arnaud-Fassetta, 2003; Liébault and Piégay 2002). In Italy, Surian et al. (2009) detected small width changes during the 19th century, but with no significant trend. From the end of the 19th century to the 1980s/1990s, channel narrowing and incision occurred, with particular intensity after the 1950s. Finally, during the last two decades, widening sedimentation and bed-level stabilization predominate, although some river reaches are still narrowing.

In Spanish rivers, discussion on the relative influence of human activities and climatic fluctuations are present in current works on palaeohydrology and flood frequencies. Several studies have indicated an increased frequency of floods in the Mediterranean region over the past centuries, with a particular rise in the 18th and 19th centuries, which they attribute primarily to climatic fluctuations during or at the end of the Little Age Ice (e.g., Benito et al., 2008; Barriendos and Martín-Vide, 1998; Barriendos and Rodrigo, 2006; Glaser et al., 2010). López-Bermúdez et al. (2002) examined the occurrence of floods in ephemeral streams at the beginning of the 20th century in the Mediterranean region, which they attribute primarily to deforestation. Additionally, important changes occurred in the second part of the 20th century dealing mainly with land use changes (Beguería et al., 2006; López-Moreno et al, 2006; García-Ruiz, 2010; Gallart et al., 2011) and torrent control works (Boix-Fayos et al., 2007). The impact of gravel mining was particularly severe in the period 1950–1980, and it is a major contributor to river incision in Spanish rivers (Batalla, 2003; Martín-Vide et al., 2010). However, there are not enough studies to establish a common chronology or to identify regional contrasts among different basins and river conditions in Spain.

Moreover, in the Mediterranean Europe, most of the research in this area has been developed in perennial rivers, where there is a permanent impact of flow on channel morphology. Less is known about river adjustments in ephemeral streams, where there are long periods of stability and a higher dependence of morphological changes on extreme or flash-flood events.

For this reason, in this paper we focus the analysis on an ephemeral stream of the eastern region of Spain. This study-case has been selected after considering several examples in the region, in most cases refused due to the extreme artificialization of channel conditions for urban, agricultural or flood control works. The aim of this paper is to provide additional information to a better understanding of the narrowing and incision processes in Mediterranean ephemeral streams. Our work quantifies morphological changes in the channel of the Rambla de Cervera over the last six decades. To achieve this goal, aerial photographs dating from 1946 to 2006 were analysed to make the following specific research contributions: (a) the identification and quantification of trends in the active corridor, bar and island changes; (b) the measurement of spatiotemporal width changes and incision; and (c) the elaboration of a conceptual cause-effect framework to define the major factors and the timing of processes affecting recent historical changes in the Rambla de Cervera.

2. Regional setting

The Rambla de Cervera rises at 1,160 meters above sea level (m a.s.l.) in the Iberian mountain range and flows 44 km in an easterly direction to the Mediterranean Sea (Fig. 1). The Cervera basin, located entirely in the Castelló Province, covers 339.6 km^2 and is mainly composed of Mesozoic calcareous rocks. The Iberian mountain range was folded during the paroxysmal compressive phase in the Oligocene, when anticlinal and synclinal structures with a NW-SE direction 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 with a NE-SW direction, that is, transverse to the Iberic folds.

The Rambla de Cervera crosses perpendicularly the mountains, being confined in horsts and expanded in grabens. The studied channel reach is 16.5 km long, 9 km in the confined sector and 7.5 km in the graben part (Figs. 1 and 2). In the mountainous area, the channel is constricted and the river adopts a wandering pattern; in the graben, lateral shift is important, and the river has a multi-thread braided pattern.

The headwaters are composed of calcareous rocks, mainly limestone, dolomies and several marls. Limestones and dolomies are hardly karstified, so they are very permeable. Calcareous aquifers are thick but very deep, a fact that favours the formation of ephemeral streams. In the graben, the rambla formed an important alluvial fan during the Oligocene. Several quaternary terraces can be located along the studied reach, especially in the graben part. The river has a slope of 1.4 % and the channel bed is mainly composed by cobbles and gravels. The average size of the surface materials is 25.8 mm, but the bed is armoured (Segura-Beltrán, 1990). The mean annual rainfall oscillates between 480 mm at the coast and 700 mm in the headwaters area. The maximum monthly rainfall typically occurs in autumn and spring, with the minimum monthly rainfall in July. The Rambla de Cervera only flows after heavy rains. In these ephemeral streams, runoff appears from two to four times a year on average and it is usually discontinuous along the channel. The combination of the basin physical characteristics (steep slopes, sparse vegetation, thin soils and permeable rock) and intense, heavy and irregularly distributed rainfall generates flash floods. Hydrographs have sharp rising limbs and short lag times (Segura-Beltrán, 1990).

In the Rambla de Cervera drainage basin, human pressure was important in the past, but has decreased in the last decades as a result of rural depopulation. The population density is very low, and it decreased considerably in the analysed period (9.2 inhabitants/km^2 in 1946 and 3.7 inhabitants/km^2 in 2006).

3. Methods

3.1. Changes in river planform

We used aerial photographs and orthophotos from different dates to investigate recent changes in the study reach. The photographs range from 1946 to 1991 and their scale from 1/43,000 to 1/18,000. The orthophoto used was taken in 2006 at a 1/5,000 scale (Table 1). The photographs were scanned at a resolution of 400 dpi to obtain average pixel dimensions of approximately 1 m (or less in a more detailed scale). The photographs were georeferenced to orthophotos using ArcGIS TM version 9.3 (ESRI, Redlands, California, 2009). To georectify the images, ground control points (GCPs) were selected from the image (for approximately 10-12 points along the river corridor). The image distortion across the near-horizontal surface of the river corridor was assumed to be parabolic and, for this reason, a 2nd order polynomial was employed for georectifying. We adopted bilinear interpolation resampling and admitted a maximum acceptable root mean square error (RMS) of less than 5 pixels. The georectified photos are affected by the georectifying error between adjacent photos, but it was impossible to correct it completely, especially in the older photographs. According to Mount et al.

(2003), we estimated errors for channel width measurements based on the aerial photograph sources. Image distortion errors (θ) ranged between 3 (1946) and 6.4 (1956) meters, whereas the location errors (pR) ranged between 1.8 (1977) and 3.5 (1956) and the mean width error (e_w) was 10.6.

The images were then interpreted to identify changes in river corridor morphology. The margins of each form were manually digitised, and an attribute table was created for the resulting polygons, including their code, perimeter (m) and area (m^2). The channel forms were classified following the conceptual model of Gurnell et al. (2001) and Zanoni et al. (2008), although some modifications were made. We identified gravel channel, incipient islands, established and floodplain-dissected islands. Gravel channel are the un-vegetated branches of the river bed, frequently affected by flow. Incipient islands are gravel or cobble patches covered by less than the 20% scattered bushes and sparse grass cover. The established islands are covered by more than the 20% scattered bushes or trees and completely covered by a dense grass layer or are occupied by crops (olive trees or vines). Dissected floodplain islands are the remaining parts of the floodplain incorporated to the active corridor by chute cutoff processes (Ashmore, 1991). These islands differ from those established by the alignment of the crops and plots on either side of the chute cutoff, and they can be identified by comparing subsequent or previous photographs. Although they are underrepresented, the chute channels have been separated from the gravel channel category because they indicate processes of floodplain dissection. The outer limit of the active corridor was defined by the boundary between areas of gravel and any remaining, extended vegetated surface that had not been classified as island at any period (Zanoni et al., 2008).

3.2. Assessment of changes in anthropogenic pressure on land

3.2.1. Archives data of human and livestock densities and agricultural uses

Historical land use changes play a major role in sediment balance and morphological channel evolution. Statistics on population and livestock densities can be used to examine anthropogenic pressure on the environment. Population data of Rambla de Cervera basin have been obtained from modern census. The first was conducted in 1857, the second in 1877 and subsequently census have been published regularly at intervals of 10-11 years (www.ine.es).

The evolution of cattle farming before 1950 for the whole Castellón Province, where the Rambla de Cervera is located, has been studied by Obiol (1989). This work was based on four surveys and statistics produced between 1850 and 1962. After this year, information was obtained from the National Agrarian Census of 1999 and 2009 (www.ine.es) and Valencian Statistics Institute (www.ive.es). Provincial historical data from agricultural or soil use have been obtained from the official survey of 1850 and the National Agrarian Census of 1961. We have also information from the historical evolution of cereal crops in the headwaters area from Sangüesa and Albiol (2010).

3.2.2. Land use changes

The land uses in the Rambla de Cervera basin between 1946 and 2006 were mapped and seven land use types were selected to classify the study area: (i) urban areas; (ii) forested areas, including holm oaks, coniferous and mixed forests; (iii) bush or shrub areas; (iv) rainfed annual crops, which are almost entirely cereals; (v) rainfed cultivated trees, mainly represented by olive groves; (vi) sparsely vegetated areas, also including small bare rock patches and recent burnt areas; and (vii) river beds.

In most cases, the interpretation of land patterns was facilitated by relatively small pixel dimensions (between 1.15 and 0.5 m). The limit between the categories of bush and forest was established in the 50% of forest strata coverage.

The basin was divided in two sectors to provide a better interpretation of the sequence of land use change linked to the geographical contrasts (Fig. 1). The upper sector encompasses the basin located upstream of the highest point of the Rambla de Cervera study reach, over the horst area. The central sector covers the basin area downstream of this point, providing lateral inputs to the river channel study area.

3.2.3. Gravel mining data

Two companies have been extracting gravel from the Rambla de Cervera during the last decades, but only one of them has exploited the study reach. Extractions started in 1972 in this area. Gravel mining data are difficult to obtain because the administration did not register continuous and standardised information on mining concessions in recent decades, and they did not control extractions rigorously. We have obtained different information from the administration: (a) annual data between 1980 and 1988 (Pardo, 1991); (b) total data of the periods 2000-2005 and 2006-2007 (information obtained from the *Confederación Hidrográfica del Júcar*) and (c) no data between 1972 and 1979, and between 1989 and 1999. These data reflect the amount of gravel extracted by the two companies working in the river, impeding the quantification of the amount extracted in the study area. Photo-interpretation and local interviews were conducted to contrast official data.

3.3. Channel elevation and channel width measurement assessed by topographic survey and aerial photographs

Channel width can be defined in different ways in a braided network, but in this study width is the result of measuring the total un-vegetated width. That is, channel width has been considered the sum of the single channel branches widths, plus the un-vegetated gravel bars (Bertoldi et al., 2009; Michalková et al., 2010). It was measured on the aerial photographs every 500 m along the entire study reach (16.5 km).

The incision was measured indirectly from a survey conducted in 2011 on the first 10 km of the study area. The measurements were made using GPS-RTK (accuracy of 15 cm), and they covered an area of 314,400 m^2 with 9,242 points (0.029 points/m^2). A DEM of 1 m resolution generated from survey data was used to make cross sections. The active corridor of 1946, 1956, 1977, 1991 and 2006 was used to define the external limit of channel courses during the last 60 years. Using ArcGis Spatial Analyst tools, we calculated numerous profiles, selecting eleven of them considered optimal for incision estimation (Fig. 2). The distance between them is variable and different for those sections were width was calculated. The necessary conditions for selection were: a) sections where the corridor has narrowed in all the periods; b) clear channel boundaries; c) boundaries coincident with microterraces, identified trough photointerpretation and field works (Fig.2). The incision was calculated in each section measuring the height of the boundary channel each year (1946, 1956, 1977, 1999 and 2006). Stereoscopic analysis and fieldwork contributed to corroborate the information provided by cross sections analysis. The topographic survey took place in 2011 but we assume that incision has not increased since 2006, because no significant flow event occurred during the last six years.

3.4. Flood estimation and rainfall data

The Rambla de Cervera is an ungauged ephemeral stream. The flow is scarce, and the circulation is mainly local due to the high infiltration of the calcareous substrata and the transmission losses. Adjoining catchments, such as the Cervol River (349 km^2) and the Bergantes River (1,201 km^2), has been gauged in the past and it is possible to define their hydrological characteristics. We assume that these hydrological parameters are similar to the Rambla de Cervera basin:

- The Cervol gauging station was active between 1911-1929, with ten complete years and nine incomplete. It has been used to analyse floods in previous works in the region (Segura-Beltrán, 1990; Camarasa-Belmonte and Segura-Beltrán, 2001). The runoff production in this calcareous catchment is not higher than 17% of the rainfall. In this area, the average runoff threshold for the drainage basin is 65 mm, but it varies significantly between different rainfall events in the same basin (35 to 65 mm) depending on factors such as lithology, type of soil, vegetation cover and rain intensity and duration. Flash floods occur when rainfall exceeds this threshold, although in many cases they only have a local effect due to the transmission losses. Bankfull floods are scarce, but they can produce significant modifications to the channel forms.
- According to the geographical conditions, the Bergantes gauging station (active forty years between 1931 and 2007) is representative of the hydrological behaviour of the Rambla de Cervera headwaters. It has been used to analyse historical flow discharges evolution.

Moreover, the most relevant floods of the Cervol River and Rambla de Cervera have been reconstructed using three data sources: archives and newspapers, rainfall data and stream flow gauging data. In addition to this, in order to investigate whether the morphological changes of the river channel were correlated with a reduction in channel flow, we have analysed possible changes of the rainfall regime. We have considered rainfall series from three weather stations (Table 2).

- Morella (1920-2010) (1.010 m a.s.l.) is representative of the climatic conditions of the headwaters sector, with mixed continental and Mediterranean rainfall pattern.
- Sant Mateu and Sant Mateu HS (322 m a.s.l., both located at the same village and complementary), representative of the climatic conditions of the study reach. Closer to the sea, they present a rainfall Mediterranean regime, with a clear autumn rainfall peak.

Climatic series were studied in different ways: (i) annual rainfall trends for the whole record of each weather station; (ii) total rainfall events higher than 65 mm, assuming that this threshold establishes the minimum rainfall for runoff production in the region. Climatic series were studied in several time windows: a) 1920-1935 and 1936-1945, to define the rainfall regime previous to 1946; b)1947-1956, 1957-1977, 1978-1991, 1992-2006, to analyse the intervals between the aerial photographs. The existence of trends in the climatic variables was tested using the Mann–Kendall test (Yue et al., 2002; Boix-Fayos et al., 2007) applied on average annual rainfall for the whole time interval of each rain gauge data set.

4. Results

4.1. Channel morphological changes

The analysis of surface percentage occupied by different active corridor units presents different morphological trajectories (Fig.3). The gravel channel area underwent the most important changes along the period, presenting a decline. In contrast, the established islands had growth in the total period, whereas the incipient islands maintained a similar percentage in the different periods, acting as a transitional stage between the previous units. The islands attached to the floodplain fluctuated but reached their maximum development at the end of the period. Finally, chute channels and floodplain dissection islands were represented until 1977 but disappeared in recent years. They were not significant along the studied period, but their evolution is relevant because they are indicators of lateral mobility processes and channel widening.

The most commonly observed trend began when incipient islands were formed in some gravel patches covered by grass and scattered bushes. Further accumulation and growth of vegetation, woody debris and sediment around these incipient islands supported their enlargement and coalescence, culminating in the formation of larger established islands. In some cases, early occupation by crops helped to fix the established islands. These trajectories reflect floodplain construction processes, through the progressive reduction of the gravel channel by the lateral growth and the relative elevation of islands.

Reverse processes have also been found locally. In some areas and periods, floodplain destruction is produced as a consequence of avulsion processes. Chute channels develop and dissect the floodplain, producing established islands. In other cases, these islands are partially eroded and transformed into incipient islands, which in turn can become channels because of lateral shift, losing vegetation.

According to these observed trajectories, the changes were classified as constructive or destructive in order to analyse the turnover between the different forms. Surfaces were calculated for each category, and the most significant values (> 4%) are shown in Fig. 4.

The constructive and destructive changes occurring in the active corridor are mapped in Fig. 5. Floodplain constructive processes predominate over the whole period, but four stages have been identified:

- 1946-1956. Floodplain constructive trajectory prevailed. The most notable processes were the turnover of the gravel channel in the incipient and established islands.
- 1956-1977. Period with a mixed evolution that nearly equals the constructive and destructive trends. The channel grew at the expense of islands and bars in some areas, whereas in others it turned into incipient islands or became established islands.
- 1977-1991. Clearly constructive period. The channel evolved into incipient islands and these to established islands. Stability mainly affected the established islands, which for the first time exceed the gravel channel.
- 1991-2006. Period with mixed trends. Destructive processes affected a larger surface, but numerous incipient islands were transformed into established islands, and these were attached to the floodplain.

4.2. Width change trend

The measure of the channel width shows a progressive reduction through time, from the first available measurements in 1946 until 2006, when the channel width reached a minimum (Fig. 6). During this period, the mean width of this reach decreased from 214.6 m to 67.6 m, a reduction of 68.5%. The most important width reduction (46%) took place between 1946 and 1956. This trend was interrupted in the period 1956-1977, when the channel width slightly increased by 2.9% and gravel channel area by 2.3%. Between 1977 and 1991, the channel area decreased by 19.9% and width channel by 39.8%, and in the last period there was a small channel area loss of 2.4%.

The spatiotemporal distribution of changes is shown in Fig. 6. The reduction of the first period affects the whole study reach. A similar behaviour is observed during the other decreasing period (1977-1991). However, between 1956 and 1977 there was a narrowing process in the horst sector and a marked widening process in the graben reach. A similar behaviour was observed, though to a lesser degree, in the period 1991-2006.

4.3. Channel incision

The channel incision analysis indicates marked streambed degradation (Fig. 7). The average bed incision of the study reach is 3.5 m. The annual incision ratio between 1946 and 2011 is 0.054 m/year, although there are important differences between the four periods. The highest incision rates took place after 1977: 0.088 m/year (1977-1991) and 0.081 m/year (1991-2011). During the two first stages incision was less intense 0.028 m/year (1946-56) and 0.021 m/year (1956-1977). A deeper view shows that incision between 1946 and 1956, despite the mean values, was exclusively detected in two sections, P4 (0.5 m) and P7 (2.4 m), as it has been confirmed through a stereoscopic analysis. During the whole study period, the highest incision occurred in these sections, where general processes overlap some local factors. The first one (P4) was located in the narrowest section of the study reach. At this point, the hydraulic radius is high, enhancing incision during floods. The second (P7) presents the maximum streambed degradation (6.44 m), reflecting incision in all the studied periods. At this point, located immediately downstream of a 250-m-long bridge built in 1933, a knickpoint has been detected (between P6 and P7, fig. 2 and longitudinal profile, figure 7a). The incision was probably partially previous to 1946 and it was mainly caused by local scour of the

CV-312 bridge (longitudinal profile, figure 7a). The concrete footing of the bridge acted as a dyke, stopping the headwater erosion and hindering knickpoint regularisation. In fact, the lowest values are found at 5.5 km (P6), located upstream of the bridge, where the bed lowering is 1.75 m. The flood of 2000 destroyed this bridge (Fig.8) and other located downstream, by undermining, despite having been reinforced many times during the study period.

5. Causes of channel changes

5.1. Climatic and hydrological changes

The analysis of rainfall series detected no significant variations in mean annual rainfall in the Rambla de Cervera basin and no trend in daily rainfall (Fig. 9 a and b). The test of Mann-Kendall has no trend for annual rainfall for the whole of the period in Morella (Z_k= -0.011, p= 0,990) and Sant Mateu-Sant Mateu HS (Z_k = 1.207; p = 0,227) in any time window. The analysis of the Bergantes River discharge, shows a smooth negative trend, but with low significance (Z_k= -2.274, p = 0.0229). This indicates that, although the rainfall remains stable (Morella), river discharge has slightly decreased, influenced by other factors.

The analysis of rainfall events higher than 65 mm shows important spatio-temporal differences in both weather stations. In Morella, representing the headwaters area (Fig. 10 a), there was a high frequency of events (17) exceeding 100 mm in the period 1920-1935, whereas in the following period there were only 4 events and 6 events between 1946-1956. Between 1956 and 1991 rainfall events between 100 and 200 mm increased, and several events between 200 and 400 mm were recorded. In the last period (1991-

2006) events between 100 and 200 mm have increased. In Sant Mateu-Sant Mateu HS, located beside the study reach (Fig 10 b), there is a higher frequency of events for the overlapping period, particularly important between 1956 and 1991. The most frequent events are those between 100 and 200 mm, but there are also some events between 200 and 400 mm, mainly in the central period.

Flow data from the adjoining gauged rivers, although partial and without statistical representation, has helped us to reconstruct the recent hydroclimatic variability.

The historical floods of the Cervol River (Table 3) were frequent during the last quarter of the 19th century and the first quarter of the 20th century (Borrás, 1928). When the river was gauged, between 1911 and 1929, the year 1920-1921 was particularly significant. The river flowed almost during the whole year and important flow peaks were registered. After 1920, we have also information from the Rambla de Cervera, whose floods have coincided with similar events in the Cervol River.

Thus, for the whole basin, a strong variability of large floods is inferred from the available historical and rainfall data: a) between 1919 and 1956, there is a period of high flood recurrence (1919-1929), followed by a period of scarce events (1935 and 1945) (Morella); b) an increase of floods between 1956 and 1991, particularly in the period 1956-1977 (Sant Mateu-Sant Mateu HS); c) a smooth decrease between 1991 and 2006.

5.2. Population and livestock density

Historical changes in population and livestock were analysed as indirect indicators of land use change before 1946. The Rambla de Cervera basin is located within a rural district that was seriously affected by depopulation and a traditional dry-farming crisis. The historical maximum population of the basin was in 1900, with 18,112 inhabitants

(Fig. 11). The population decreased by 25% in 1950 and 50% in 1991. In 2001, this trend has slowed down and the total population has reached 8,323 inhabitants. Ovine and caprine breeding, characteristic of this region, fluctuated through time linked to economic and political events (Fig. 11). Experts have detected a peak of ovine breeding after the Philloxera crisis of 1902 in the whole Province of Castelló, when numerous farmers abandoned grape production (Obiol, 1989). Since then, the livestock decreased markedly until the 1960s. Only after the 1990s there is a smooth recovery of this activity due to farming subsidies, but during the last decades grazing has been replaced by on-farm feeding practices, with no direct impact on hillslope vegetation. Agrarian statistics follow a similar evolutionary trend. In the municipality of Morella, the area of cereals reached a maximum in 1917 (7,215 hectares), over the less productive high lands, through terraces construction (Sangüesa and Albiol, 2010). Land abandonment was particularly intense between 1950 and 1970, during the depopulation crisis of the region (from 6,018 hectares in 1953 to 1,889 in 1975). In 2011, the area decreased to 1,171 hectares (www.ive.es).

5.3. Land use changes from aerial photographs

Depopulation processes lead to the abandonment of agriculture and the natural regeneration of vegetation. Consequently, forested areas have increased considerably, doubling in the period 1946-2006 from 3,847 to 8,154 hectares (from 15.3 to 33.1%). Most of this increase took place in the headwater area, where the progressive abandonment of extensive mountain exploitation practices (grazing and fuel wood collection) led to the regeneration of holm oaks (*Quercus rotundifolia*) and coniferous (*Pinus halepensis*) forests (Figs. 12 and 13, and table 4).

Bush presents an apparent stability, with 9,305 hectares in 1946 and 9,719 hectares in 2006. However, a detailed analysis shows important changes in this category, which behaves as a transitional stage between the cultivated plots and the forest cover. The separate analyses of both basin sectors reflect these changes. In the headwater area, bush decreased from 6,726 to 4,535 hectares between 1946 and 2006 (from 55.6 to 35.6%), whereas forest increased from 3,211 to 6,346 hectares (from 26.6 to 52.6%). In contrast, in the same period and in the graben sector, bush increased from 2,589 to 5,184 hectares. Arable lands, including rainfed trees and cereals, decreased from 42.1% to 24.3%, boosting afforestation processes. Thus, land use change trends suggest a change in runoff and sediment balance, reducing the impact of rainfall on flow and sediment generation. Opposite pattern changes, such as the small increase of urban area (from 43 to 97 hectares between 1946 and 2006), are not relevant.

5.4 Gravel mining instream

According to the official data (Table 5), corresponding to the whole Rambla de Cervera Channel extractions between 1980 and 2007 total 358,040 m^3, with a ratio of 7,984 m^3/km of length. Gravel mining was intense between 1980 and 1988, reaching an average of 36,600 m^3/year, whereas during the period 2000-2007 extractions decreased to 3,500 m^3/year. As we have stated above, these data are partial and incomplete, but interviews and photo-interpretation enable to corroborate the observed general trend. Gravel mining started in 1972 and reached maximum values during the decade of 1980s, when the administration did not establish restrictions. After this decade, the gravel extracted from the river has decreased progressively (to a tenth part in the period 2000-2007), because the administration has intended to reduce the impact of gravel mining on rivers and the companies have started exploiting former agricultural plots in the floodplain.

6. Discussion

6.1. Conceptual model of evolution

According to the available hydro-climatic references and the information about human-induced changes, we attempted to conceptualize the evolution of the channel of the Rambla de Cervera:

- **Prior to 1946**. The lack of aerial photographs from the first part of the 20th century makes it difficult to assess the evolution. However, some evidences prove that the environmental and climatic context was different to present conditions (Fig. 13). The maximum population density and the maximum agrarian land use took place at the beginning of the 20th century. Therefore, the mountains had scarce and sparse vegetation, and were exposed to heavy rains, increasing runoff and sediment supply. Moreover, historical floods registered between 1919 and 1930 suggest a trend of high recurrence, such as in other Mediterranean rivers after the end of the Little Ice Age (Benito et al., 2008; Barriendos and Martín-Vide, 1998; López-Bermúdez et al. 2002; Barriendos and Rodrigo, 2006; Glaser et al., 2010). As a result of this, channel aggradation processes most likely took place.

In the 1930s, population and cattle farming decreased and hillside conditions should started to change due to vegetation recovery, reducing runoff and sediment availability, as it has been observed in other Mediterranean rivers (Hooke, 2006; Piégay et al., 2004, 2009; García-Ruiz and López-Bermúdez, 2009; García-Ruiz, 2010). Nevertheless, after the large floods of 1935 and 1945 the river could maintain an aggradational morphology, which is still reflected in the 1946 aerial photographs (Fig. 14). In these images, taken in the winter of 1946, the sediments from the recent 20th of November of 1945 flood cover former established islands, occupied by agricultural plots. This aggradational behaviour suggests that: a) the reversion of land use trend was still insufficient to alter significantly the sediment availability and, b) the channel adjustment period to watershed land-use changes is long.

- **1946-1956**. The most important changes in the river planform took place in this period. Channel width and area decreased (46% and 26% respectively) and the incipient and established islands area was tripled (Fig. 14). Incision was not significant (0,028 m/year), and only was detected in two points (P4 and P7), caused by local factors.

The narrowing process took place in a context of radical decrease of agriculture and overgrazing, which stimulated natural hillslope reforestation. Similar changes have been also identified in French, Italian and Spanish rivers as a response to spontaneous or man-made reforestation processes (Liébault et al. 2005; Boix-Fayos et al., 2007; Piégay et al. 2009; Preciso, et al. 2011; García-Ruiz and Lana-Renault, 2011). Rozin and Schick (1996) also documented significant narrowing in this period in Nahal Hoga, an ephemeral stream of the southern coastal plain of Israel. However, in this study case, the lack of large floods between 1946 and 1962 appears to be the major factor inducing channel narrowing processes. In the Rambla de Cervera, the absence of flow over the river bars facilitated terrestrial vegetation colonization and incipient islands development, reducing progressively the gravel channel. The aerial photograph of 1956 clearly reflects this process, which probably continued until 1962, due to the lack of floods.

-**1956-1977.** In this period, there was a smooth inversion of previous trends. The channel width and surface increased 2.9% and 2.3% respectively to the detriment of incipient and established bars, and the floodplain dissected islands. Incision was still moderate (0.021 m/year).

The local newspapers and the analysis of rainfall have documented a period with an important increase of flood events (1962, 1964, 1965, 1967 and 1971). Crop abandonment and natural reforestation progressed. Gravel mining in stream started in 1972, just after the last flood event of this period. For this reason, this activity had no significant impact on the river during this stage.

The action of recurrent large floods over a not incised channel facilitated the destruction of consolidated islands, and also the avulsion and formation of dissected floodplain islands, causing a small enlargement of the gravel channel (Fig. 14), especially in the graben area. Partial reversals of temporal trends have been related to the occurrence of high magnitude floods or to periods within which are a relatively high frequency of significant flow events, in French rivers during the 1990s (Piégay, et al., 2009) and in Italian rivers (Rinaldi et al, 2009; Surian et al., 2009; Zanoni et al., 2008).

- **1977-1991.** This period represents a second stage of channel area decreasing (19.9%), gravel channel width narrowing (39.8%) and, especially, of maximum channel incision (0.088 m/year). Headwaters vegetation recovery progressed, due to land abandonment and natural regeneration processes. Livestock stopped decreasing, but grazing was replaced by on-farm feeding practices, with no impact on natural revegetation processes. The sediment deficit increased due to the impact of gravel mining, which severely affected the channel dynamics and boosted previous natural and human-induced changes. The sequence of important floods was not capable of modifying the narrowing trend.

- **1991-2006**. In this last period, channel narrowing slowed down and even a small enlargement is detected in some points (Fig. 14). Incision reached high values (0.081 m/year). The environmental conditions were similar to the previous stage, and hillslope reforestation reached maximum values. Gravel mining decreased considerably, disappearing in part of the study reach.

The high-magnitude rainfall events decreased, but one of the most important floods of the last century was registered in October of 2000 (Table 3). The dual behaviour observed in the period most likely corresponds to two overlapping processes. On one hand, the extraordinary flood of October 2000 was most likely responsible for the smooth growth and widening of the gravel channel in some sectors. On the other, the lack of sediment supply, induced by both hillside reforestation and the intense previous gravel mining activity, enhanced incision, leaving the bars and the floodplain as a raised surface.

The previous periods' division is obviously conditioned by the availability of aerial photographs and does not represent real milestones in the development of the river. Considering this fact, it is possible to distinguish four stages summarizing the previous model: a) prior to 1946, the river had a clear aggradational behaviour, clearly reflected in the aerial photographs; b) between 1946 and 1962, there is a narrowing stage. The Rambla de Cervera underwent the longest period without floods in the century, fact that boosted the vegetation colonization of a large part of the river, reducing drastically the channel width, as it is reflected in the 1956 aerial photograph; c) between 1962 and 1972, the high recurrence of floods contributed to a smooth readjustment of the channel width and generated a slight incision; d) after 1972, there was a clear incision stage and a moderate width narrowing. The intense gravel mining, which took place in a context of advanced hillside reforestation, boosted severe incision in the Rambla Cervera, due to a drastic reduction of sediment supply.

6.2. Magnitude of river adjustment

Channel adjustment values in the Rambla de Cervera are comparable to those observed in other Mediterranean rivers. Mean incision values (3.5 m) are similar in Italian perennial rivers (3-4 m) (Surian and Rinaldi, 2003; Gurnell et al, 2012; Preciso et al. 2011; Rinaldi et al, 2009; Surian and Cisotto, 2007; and Surian et al., 2009), French rivers (1-5 m) (Liébault et Piégay, 2002; Bravard et al., 1997; and Arnaud-Fasseta 2003), and Spanish rivers (0.6-5.5 m) (Boix-Fayos et al., 2007; Martín-Vide et al, 2010). These values range in the same order of magnitude that those observed in ephemeral streams in the USA (Rinaldi et al., 2005; Cadol et al., 2011) and Israel (Rozin and Schick, 1996). The time sequence is in most cases similar: incision is detected in the 1940' and increases later, especially in those rivers where gravel mining progresses (Rinaldi et al., 2005).

The Rambla de Cervera narrowing values are also similar to other Mediterranean areas (Boix-Fayos, et al., 2007; Liébault et Piégay, 2002) and present an analogous trend, with higher levels before the 1970s (Surian et al., 2009). In general terms, the Rambla de Cervera results are particularly similar to those obtained by Rozin and Schick (1996) in Nahal Hoga, a small Mediterranean-semiarid ephemeral stream. Despite the different causal factors, both cases share an initial aggradational stage previous to 1946, a marked narrowing period between 1945 and 1956, and a slight readjustment in the subsequent flooding periods, parallel to severe incision.

6.3. Spatio-temporal variability of adjustments in ephemeral streams

River adjustment presents several particularities in ephemeral streams, which arise from the discrete nature of flow events. Moisture antecedent conditions, land use changes and soil properties, spatial and temporal variability in rainfall intensities, totals and annual number of events (Camarasa-Belmonte and Segura-Beltrán, 2001) and transmission losses (Thornes, 1976; Shanon et al. 2002) result in high spatio-temporal variability of discharge and sediment supply. Adjustments are caused by limited and infrequent flow events and little changes take place in between events (Wolman and Gerson, 1978). These facts may contribute to produce adjustments with high spatio-temporal variability, longer reaction and relaxation times, and higher asynchrony between causal factors and channel adjustments. Channel adjustments of the Rambla de Cervera respond to these conditions, and present certain particularities concerning the temporal variability of narrowing adjustments, the different impact of flood events and the role of vegetation in channel adjustment.

6.3.1. Temporal variability of width adjustments

Changes in the channel width are related to the contrasted effects caused by large and minor events in ephemeral streams. Large floods exceed the critical shear stress for erosion, transport larger amounts of sediment through the system and produce channel changes whose effects may persist for many years. Minor events not always exhibit the shear stress required to mobilize the channel-bed material, and therefore, could contribute to narrowing and stabilisation by vegetation (Hooke and Mant, 2002). Thus, during the dry periods, vegetation can easily colonize bars and islands, boosting narrowing processes. This could be the main cause of the radical narrowing documented in the Rambla de Cervera between 1946-1956, similar to the Nahal Hoga case study

(Rozin and Schick, 1996), attributed to a decrease of 9% in the ratio rainfall-runoff between 1940 and 1960.

On the other hand, large floods or intense sequences of large floods, such as the period 1962-1971 or the flood of 2000 in the Rambla Cervera, slowed or stopped the narrowing trend, due to the erosional work carried out in some areas of the river bed. These large events are responsible for the major channel changes, and in many occasions only mobilize material from the river bed (Hooke and Mant, 2002).

6.3.2. Different impact of flood events

With very similar rainfall inputs and opposed environmental conditions, the effects of the floods of 1935 (474 mm) and 2000 (511 mm) (Table 3) were very different. The 1935 flood caused streambed aggradation (still observed in the 1946 aerial photographs) (Fig. 14), whereas the 2000 flood provoked a marked incision and the undermining of two bridges. The first flood took place over a river basin barely vegetated, with a high sediment supply and an aggradational river bed, whereas in the second one there was an important sediment supply deficit (Fig. 13). It was generated in a forested headwater, with densely vegetated hillslopes and a river channel seriously affected by gravel mining extractions.

Despite the evident importance of changes in the environmental conditions, induced by revegetation processes or gravel mining, some of the observed incision and narrowing could also be attributed to a hydraulic adjustment to channel pattern changes. In the study reach, floods were particularly intense in 1962-1971 and 1982-1988 (table 3). However, the obtained results show the first ones widened the corridor while the second ones did not. The efficiency of these processes depends on the elevation of the islands (Gurnell et al, 2012). With similar flow values, some floods could easily generate bankfull flow whereas others, due to channel incision, only caused sub-bank-full flow. Thus, the 1962-1971 floods occurred on a river bed slightly incised, so the flow could pass through consolidated bars, opening new channels (Fig. 14). Nevertheless, during the 1980's, as incision progressed, the islands were relatively elevated, and then, the river flow was concentrated in a major hydraulic radius, increasing incision and reducing the impacts on the established islands. Only the large flood of 2000 was capable to combine incision impacts with some local enlargement of the river channel, due to its higher magnitude.

6.3.3. Vegetation and variability in adjustment changes.

In ephemeral streams, the interaction of floods sequence and vegetation development proves to be a major factor in channel morphology changes. The evolution of vegetation depends on the regime of the spatio-temporal sequence of flood events, rather than the statistical frequency, whereas changes in channel morphology are partially determined by the distribution of vegetation (Hooke and Mant, 2002). Thus, in ephemeral streams, the lack of flow for long periods preserves vegetation development, boosting colonisation and channel narrowing processes, as it has been detected in the Rambla Cervera between 1946 and 1956.

The evolution of the Rambla de Cervera is similar to the model proposed by Mant (2002). The colonisation of vegetation in a high-energy environment begins with herbs, most frequently found in mid-channel areas. Herbs and terrestrial bushes initiate the island's colonisation (*Rosmarinus officinalis, Thymus vulgaris, Ulex parviflorus*), whereas *Salix* or *Pinus* only appear in the second stage, especially when the islands are attached to the floodplain. As a result of this process, incipient islands comprise a mixture of shrubs and large grasses, and higher species diversity is found on consolidated islands and flooplain, where flow events are less frequent and plants are also associated with agricultural land.

The agricultural use of islands plays an important role. Farmers fix the islands with vineyards, olive groves and dry-stone walls, usually perpendicular to flow direction. After the floods, if the flow has covered the fields, farmers restore their plots. Figure 14 shows an example of island restoration and expansion caused by agricultural uses, frequently repeated along the study reach. This process is particularly frequent and successful in those islands attached to the floodplain, probably because farmers have a lesser perception of risk in the river side.

Variation in channel confinement and their effect on stream power can also have a strong influence on vegetation distribution. Confined reaches have higher unit stream powers, and the vegetation is more likely to suffer flood damage than less confined reaches (Sandercock et al., 2007). In the Rambla de Cervera, where there is a contrast in channel confinement between the graben and the horst area, we have observed a different development of vegetation colonization. The non-confined areas of the horst sector exhibit higher vegetation colonization advances and, consequently, more marked narrowing than the confined areas.

7. Conclusions

In this paper, we have analysed the morphological evolution of the Rambla de Cervera during the last six decades. In some sectors, the Rambla de Cervera has changed from a braiding pattern to a wandering one. A growing number of established islands have emerged, some of which are attached to the floodplain, considerably reducing channel width between 1946 and 2006 (68.5%). Channel shrinkage was particularly significant between 1946 and 1956. Moreover, incision processes took place along the whole study reach, with an average of 3.5 m, and it was particularly important after 1977, with a ratio of 0.08 m/year.

Both climate and human activities underwent important fluctuations since the beginning of the 20th century, although it is impossible to exactly determine the influence of each of these factors on the river's morphological evolution. Some of these factors produce contradictory effects, affecting flow, sediment dynamics and vegetation cover.

Short- term channel adjustments are mainly depending on magnitude, frequency and timing of the floods. Long-term changes are influenced by sediment fluxes, flow and flood characteristics and interaction of sediment and vegetation. In general terms, the alteration of sediment fluxes has been a major factor driving such channel adjustments, and it was mainly caused by land use changes and gravel mining. The absence of flow and the randomness of floods have determined the rhythm of river adjustment processes, mainly through the active corridor vegetation encroachment. Irregularity of flow and the randomness of large flood cause long periods of stability and very long reaction times, whereas disturbance take place in very short time lapses. As a consequence, these processes are more discontinuous and irregular than in perennial rivers.

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Figure captions

Fig. 1. Sketch of location: a) Rambla de Cervera, Cervol River and Bergantes River basins and gauging stations; b) DEM of the basin, Rambla de Cervera (dashed white line), study reach (continuous white), and weather stations located in Morella and Sant Mateu. Dashed black lines subdivide the Rambla de Cervera basin in three sectors, upper, middle and lower basin.

Fig. 2. Sections where incision and width were measured. The channel width (the sum of the single branches widths) has been measured each 500 m. Eleven sections were selected in order to measure incision processes. The hillshade map shows the contrast between the horst and the graben area. Above, river section number 10 is shown to present the methodology for river incision calculation. Several microterraces have been identified, through photointerpretation and field works, to quantify incision.

Fig. 3. Evolution of the corridor forms in the Rambla de Cervera study reach (1946-2006). Gravel channel significantly decreases, whereas established islands increase.

Fig. 4. Evolutionary trends of corridor morphological units. The numbers express percentages of the fluvial corridor surface (>4%) moving from one category to another or remaining stable. Floodplain construction trajectories reflect gravel channel evolving to incipient islands and these to established islands. Floodplain destruction trends are

the inverse processes. There are two floodplain construction periods (1946-1956 and 1977-1991), and two periods with mixed performance (1957-1977 and 1991-2006).

Fig. 5. Spatial distribution of changes in the active corridor. Floodplain construction trajectories are those contributing to reduce the active corridor and floodplain destruction trajectories, those enlarging the active corridor.

Fig. 6. Accumulated channel width change. Above, presented in box plots (a) and below (b), reflecting spatiotemporal variability. Most significant changes took place in the graben area, where the lateral shift of the Rambla de Cervera was higher. Channel width change was particularly marked in the period 1946-1956.

Fig. 7. Incision (m) estimated in eleven selected sections of the study reach. Above (a) longitudinal profile. Below (b) accumulated incision in different cross-sections. The highest incision (p7) is located downstream of the only bridge across the study reach.

Fig. 8. Picture taken immediately after the 2000 year flood at the CV-312 Bridge, reflecting undermining and incision processes in p7.

Fig. 9. Rainfall series (24 hours) of a) Morella and b) San Mateu weather stations. No trend is observed in annual mean rainfall.

Fig. 10. Temporal distribution of rainfall events classified per total rainfall (mm) in a) Morella (upper basin), and b) Sant Mateu-Sant Mateu HS (middle basin). The number over the bars is the number of events higher than 65 mm, regional threshold to produce runoff. Graphic a (Morella) shows a scarce number of events between 1935-1946 and an increasing number of events in 1991-2006. Graphic b (Sant Mateu) shows a high number of events throughout the whole period, particularly between 1956 and 1977.

Fig. 11. Evolution of population in the Rambla de Cervera basin and ovine-caprine cattle in the Castellón Province.

Fig. 12. Land use changes in the Rambla de Cervera basin between 1946 and 2006.

Fig 13. Spontaneous reforestation processes are also reflected in historical pictures. The above two pictures were taken by J. Martínez Sánchez between 1865 and 1867. Below, the same area in 2011. The arrows join common points.

Fig. 14. Evolution of corridor forms in a representative reach of the study site. The 1946 image shows how the flood of 1945 covered an agricultural consolidated island with gravels. In 1956, the crops had been restored and there were new plots exploited. In 1977, floods had divided the island in two, destroying partially the fields. Only after 2006, the island seems to be lifted enough to avoid the impact of new floods. This island elevation has been, in this and other cases, stimulated by gravel mining on the river channels. Sketch (a) shows recent incision processes eroding red Pleistocene conglomerates, below the Holocene and historical gravels. Reforestation processes can be observed in the lower part of the images, where agricultural plots are progressively colonised by bush and *Pinus halepensis*.

Fig. 15. Trends of river adjustments, main human disturbance factors and natural reforestation causing bed river changes.

Table 1. Summary of data sources used for the analysis of channel and basin changes.

Table 2. Rainfall series characteristics in the weather stations of the study area.

Table 3. Historical floods registered in Cervol River and Rambla de Cervera. Total rainfall events (mm) has been obtained from Morella weather station and Qmax from Cervol gauging station.

Table 4. Land use evolution in the basin of the Rambla Cervera study reach (hectares).

Table 5. Gravel extracted from the Rambla de Cervera according to the official data. Data between 1980 and 1988 has been obtained from Pardo (1991). Nd = no data. Data between 2000 and 2007 has been obtained from information of the Confederación Hidrográfica del Júcar.