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Recent human impacts and change in dynamics and morphology of ephemeral rivers

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Abstract. Ephemeral streams induce flash-flood events, which cause dramatic morphological changes and impacts on population, mainly because they are intermittent and less predictable. Human pressures on the basin modify load and discharge relationships, inducing dormant instability on the fluvial system that will manifest abruptly during flood events. The flash-flood response of two ephemeral streams affected by load supply modification due to land use changes is discussed in a combination of geomorphic and hydraulic approaches. During the Rivillas flash flood, intensive clearing on the basin led to high rates of sediment flowing into an artificially straightened and inefficient channel. The stream evolved from a sinuous single channel into a shallow braiding occupying the entire width of the valley floor. Misfits and unsteady channel conditions increased velocity, stream power and sediment entrainment capacity and considerably magnified flood damage. Resulting morphosedimentary features revealed a close relationship with the valley floor post-flood hydraulic model, and pre-event awareness would have made it possible to predict risk-sensitive areas. In the second case, the Azohía stream, modelling of current pre-flood channel conditions make it possible to determine channel narrowing and entrenchment in the lower alluvial fan stretch. Abandonment of intensive agriculture, basin reforestation and urbanization diminish load contribution and trigger channel incision. This induces an increase in slope and velocity in the bankfull channel, producing renewed erosive energy and thus activating upstream propagation of incision and bank undermining. The absence of water-spreading dynamics on the alluvial fan in favour of confinement in a single channel produces an unstable dynamic in the system, also offering a false sense of stability, as long as no large magnitude floods occur. When modelling flood-prone areas and analysing hydraulic variables, it is important to detect possible anthropic disturbances that may affect basin load budgets in order to anticipate catastrophic consequences resulting from inappropriate fluvial management before the occurrence of an extraordinary event.

1 Introduction

Ephemeral streams are less known than perennial rivers, mainly because they tend to be located in less populated, semiarid or arid environments and are only sporadically active. Therefore, there is also a general lack of information about the relationship between the causing rainfall and the resulting discharge. Ephemeral streams are, however, the ones that produce the most hazardous types of floods, due to their flash-flood nature. A flash flood is an abrupt, short-lived rise in the discharge of a stream with a dramatic contrast between the event and the extended period between floods (Reid, 2004). Flash floods are very frequent in ephemeral channels and precipitation events are typically of high intensity and spatially localized, which compounds the difficulty of obtaining rainfall registers that help to gain an understanding of the hydrodynamics of these floods (Osborn and Lane, 1969; Sharon and Kutiel, 1986; Kömüscü et al., 1998).

The geomorphic effects of flash-floods in ephemeral channels are intense since the floods are rare, but are highly efficient in producing morphogenic change, especially if the event presents a long-lasting peak discharge (Costa and

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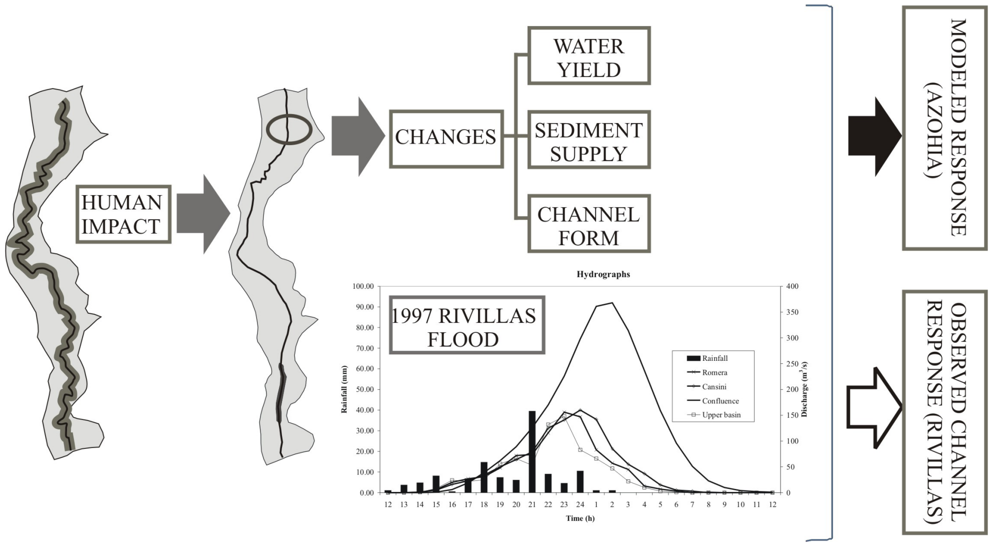

Fig. 1. Conceptual model of the study. Anthropic impacts determine changes in water yield, sediment supply and channel form that can be modelled hydraulically for an observed and hypothetic response.

O'Connor, 1995; House and Peartree, 1995; Ortega and Garzón, 2009). A flashy flow regime means that channels trend to instability, with changing morphological patterns (Conesa-García, 1995; Hooke and Mant, 2000).

There are a variety of causes inducing changes in the nature of a flood event, like storm size (Merrit and Wohl, 2003) or type of hydrological regime controlling peak flow, sediment transport and channel width (Osterkamp, 1980). There are many others, however, that may be more or less determined by human activity, such as presence or absence of riparian vegetation in channels (Tooth, 2000), effects and specific location of vegetation types (Sandercock and Hooke, 2010, 2011) and bedload, gradient and channel geometries that lead to highly turbulent flow (Kochel, 1988).

Mediterranean countries are widely affected by these ephemeral channels, including areas subject to high anthropic pressure and dense population. Dedkov and Mozzeherin (1992) consider that anthropic impacts are greater in Mediterranean streams than in any other climatic zone. This is the case of SE Spain, where flash flooding has been causing damage for centuries (Conesa-García, 1995; Poesen and Hooke, 1997; Bull et al., 1999; Camarasa and Segura, 2001; López-Bermudez et al., 2002), but also in other Iberian areas such as the Pyrenees (White et al., 1997; Gutierrez et al., 1998) or Extremadura (Ortega and Garzón, 2009). Those widely scattered areas highlight the importance of understanding flash-flood hydrodynamics in order to establish some level of prediction of sensitive areas.

Merrit and Wohl (2003) explain changes in channels as a result of aggradational (net fill) or degradational (net scour) processes, derived from wider or confined valley reaches. The relationship between channel morphology and load / discharge ratios is a key factor to understand aggrading or degrading fluvial processes. On the basis of morphological relationships derived from Lane (1955) it is possible to define fluvial response depending on load shortage or excess. Schumm (1977) proposed a river stability classification based on load modifications. Different river types would react in distinctive ways, aggrading or eroding either in channel beds or banks. This model was applied to braided or sinuous rivers, but similar responses might be expected for ephemeral stream patterns.

In the present paper we deal with ephemeral streams that are being destabilized due to anthropic changes in the basin which affect load / discharge ratios. In one case there is geomorphological and hydrological information after flood occurrence (observed response), making it possible to identify changes in water discharge, sediment supply and channel form derived from human activity (Fig. 1). In the second case we use information deduced from a similar methodology to detect changes that might be expected to result in damage in the case of a flash-flood event (modelled response).

Both selected areas are small-scale Mediterranean-type basins affected by flash-flood events (Fig. 2). The first is in the Rivillas stream (Badajoz, Spain) where a high-magnitude flood occurred in 1997. Multidisciplinary studies have been conducted, including geomorphology and sedimentology of post-flood features and hydrology and hydraulic modelling of the flood event. The second, the Azohía stream (Murcia, Spain), is a basin for which there is no information about historical flood effects. A study analogous to the Rivillas case was conducted, but prior to any flood event occurrence.

In the two case studies, hydraulic modelling was used for different reasons. In the Rivillas reach, hydraulic modelling was undertaken to calibrate one large flood event and compare it to other magnitude estimations using field data. These

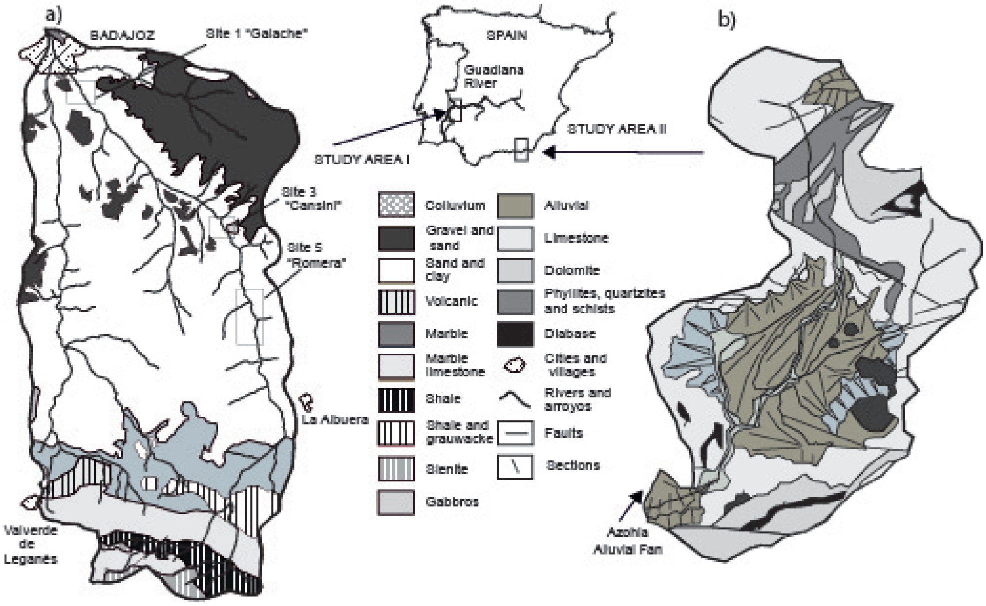

Fig. 2. Map location of the two studied areas, **(a)** Rivillas watershed and geological map, **(b)** Azohía watershed and geological map.

data were also used to compare hydraulic modelling results with subsequent morphosedimentary structures. Field surveys revealed inconsistency between the results for undisturbed floodplain reaches and areas under intense erosion or sediment supply and provided a means to interpret the drastic increase of damage due to anthropic activity. In the case of the Azohía stream, the point of departure was different. Hydraulic modelling was undertaken as a procedure for administrative flood-prone hazard zoning. This project revealed morphologically anomalous channel entrenchment, and so an attempt was made to confirm the occurrence of sensitive areas and to explain this metastable situation from the results of the hydraulic modelling.

One of the objectives of this work is to use the methodology described above to detect changes in river dynamics with the support of hydraulic variables. Our goal is to draw attention to the weaknesses of using hydraulic zoning without establishing channel geomorphic conditions and to analyse basin change analyses that may trigger abrupt modifications during a large flood.

A detailed study of aerial photos, high water marks, sedimentation-erosion processes and hydrology after a particular flood will allow us to (i) detect possible human activities that will induce changes during and after a flood event; (ii) improve floodplain zoning established by means of hydraulic models on the basis of these changes; and (iii) propose the use of this information in management and urban planning prior to flood events.

This would be applicable to areas like the Azohía Rambla where there is a lack of flood information. To that end this paper presents the changes identified in the Rivillas River basin after a medium-high magnitude flood event and extrapolates these approach results to the Azohía Rambla. Our aim is to detect changes in channel hydraulic parameters that may help to predict hazards from a future flood in an area with limited available flood information.

2 Study area

The Rivillas stream is a 34 km-long tributary of the Guadiana River, one of the largest in the Iberian Peninsula. The area presents semiarid conditions with rainfall about 400–500 mm yr^{-1} affected by frontal and convective systems. The Rivillas River has a basin of 314 km^2 and an average gradient of 0.0075 m m^{-1}.

Geologically, the Rivillas Basin is basically composed of fine-grained Tertiary detrital sediments (Fig. 2). Calcretes and some isolated gabbro outcrops occur at some points in the channel and the floodplain, constricting the floodplain flow. The geomorphology offers a gentle landscape with hills and valleys, sometimes without a well-defined river channel system. Morphometric aspects like high elongation ratio, low drainage density or a high roughness number in the Rivillas watershed suggest a predisposition to magnify the effects of storms, increasing peak discharge and flash flooding potential.

The Azohía Rambla is an ephemeral stream that spreads into an alluvial fan at its mouth on the Mediterranean Sea. In Spain, "rambla" is a term used in the scientific literature to refer to an ephemeral gravel-bed stream that is hydrologically dependent on rainfall (Camarasa and Segura, 2001). The lithological profile of the mountains (NE Betic Range) includes several sedimentary and low-grade metamorphic materials, where the complex but still active tectonics has induced abrupt slopes on the highly fractured and erodible rocks (Goy and Zazo, 1982; Sanz de Galdeano, 1983; Silva et al., 1992, 1994). Within this mountain range, Tertiary basins and Plio-quaternary valleys have developed, and that is where the Azohía Rambla and alluvial fan is located (Fig. 2). The climate is semiarid with a mean annual precipitation of 300 mm and an average temperature of 18 °C. Local conditions are influenced by the barrier effect of the Betic Mountain Range, favouring severe autumn convective storms.

The Azohía Rambla is 5 km long and its drainage basin measures 15 km^2. The drainage network is dendritic and elongated to the east and at its mouth. When it reaches the Mediterranean coastal plain, it spreads into an alluvial fan measuring 0.22 km^2 with a perimeter of 2.3 km. The Azohía alluvial fan is composed mainly of conglomerates and secondarily of sandstones produced by erosion of the abovementioned materials. The present active channel in the fan area is 15–45 m wide and 1.5 m deep with reshaped bars and human debris in the mid-final stretch. In the last 100 m, near the village of Azohía, the channel has been controlled with recently built concrete walls.

3 Methods

3.1 Laboratory analysis

Laboratory work has mainly involved measurement of the grain size of the samples collected in the field to estimate channel roughness, and geomorphological interpretation using aerial photography. We used aerial photography available on paper for different years, as well as ready orthorectified and georeferenced digital photographs available via the web (www.cartomur.es). Identification of the various geomorphological features (channels, bars, etc.) was performed with the aid of a stereoscope providing 3-D visualization of the zones. Grain size methodology consisted of a preliminary classification of samples in the field with the help of a grain size folder, followed by a laboratory analysis of 10 samples. Overall, 100 gr of each sample was treated with various cleaning reagents (Hydrogen peroxide (H_2O_2) to neutralize organic material, 50 % HCl for carbonates and oxalic acid to dissolve Fe). After drying in an oven, the samples were sieved to separate conglomerates, coarse, medium and fine sands, and shales. Finally, each fraction was weighed and the samples classified.

3.2 Fieldwork: geomorphologic survey

Prior to this study, a detailed survey of depositional and erosional features after the large 1997 Rivillas flood was required in order to compare the hydraulic model with the field observations in terms of energy expenditure and geomorphic effects. Fieldwork needs to be carried out as soon as possible after a flash-flood in order to describe the morphosedimentary features generated before they are obliterated by vegetation or human activity (Ortega and Garzón 2009). During high-magnitude floods in confined valley reaches like the one considered here, there is considerable variation in hydraulic conditions and flood hazard severity over the floodplain, especially due to complexities of morphology and microtopography (Walling and He, 1998). Post-flood surveys of high water marks (HWM) were also conducted to establish a best fit in our model. In calibrating the Rivillas flood hydraulic model, best field HWM data were selected and those showing local disturbances were eliminated.

In the case of the Azohía model no previous flood information was available. Morphosedimentary information along the present channel and alluvial fan was recorded. The data collected were grain size, presence or absence of human remnants in the stratigraphic sections, morphological field observations like valley constrictions and openings, bar reworking, secondary channels and present human interference (wells, channelization, roads and other paths and anthropic debris among others).

3.3 Hydraulic model

The Hec-ras model (Hec, 1996) was used for both sites as it is a widely used program and the one accepted in mapping Spanish flood-prone areas. This is a one-dimensional step-backwater program which uses the Bernoulli equation to model selected discharges by means of surveyed channel topography. This model has some limitations, as pointed out by Merritt and Wohl (2003), in that simulated flow is one-dimensional and in many cases these ephemeral streams have multiple flow paths, also due to the unstable nature of flash floods. We have minimized the error by considering highly detailed high water marks, which are representative of peak stages, for model calibration (Baker, 1977). Results proved to be accurate using the HWM record of the 1997 flood in the Rivillas River and the use of straight reaches with less error, as Merrit and Wohl (2003) also assume in other ephemeral river models.

The selected model discharges were the 1997 flood discharge in the Rivillas case and various return period discharge scenarios in the Azohía Rambla. For the Rivillas River, the valley slope was used as a contour condition, on the assumption that it was the same as the energy line slope; and a subcritical flow type was considered. Energy losses were calculated from roughness using Chow's tables (1959) for cultivated areas, which provided better results for the three studied reaches than the Cowan (1956) formula method. Contraction and expansion losses were estimated at 0.1 and 0.3 for sections with no geometrical changes and between 0.3 and 0.5 for sections with significant changes. There is no available gauging station to calibrate the final results, but flotsams were used as markers of the maximum flood level (Baker, 1977). For modelling in the Azohía case similar

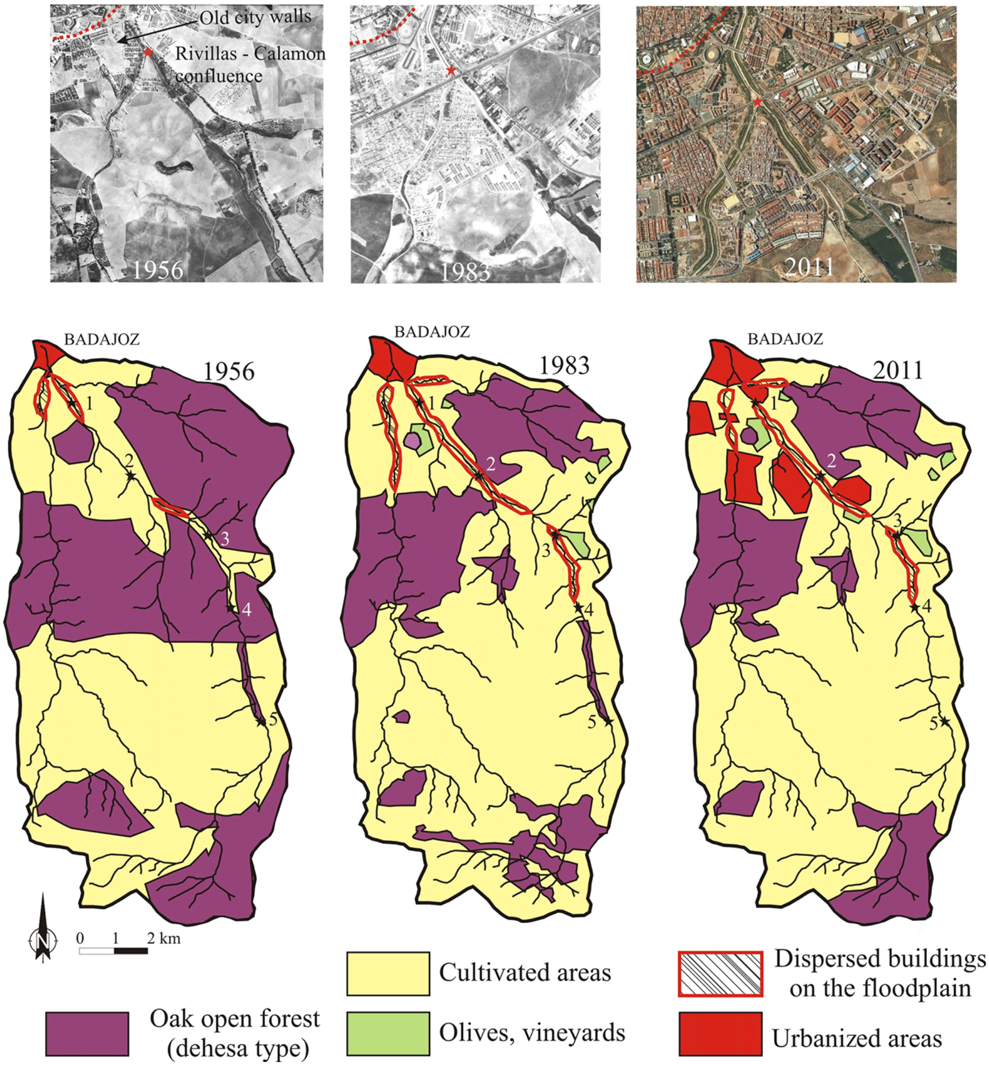

Fig. 3. Land use changes in the Rivillas Basin between 1956 and present-day based on aerial photographs and urban evolution in the Rivillas and Calamon rivers near Badajoz city. Location of studied reaches: (1) Galache, (2) Acuapark, (3) Cansini, (4) Romera, (5) Huerta Peña.

inputs were assumed, but friction coefficients were derived from Cowan's equation in view of the lack of cultivated areas. Hydraulic modelling has been shown to be useful to determine floodplain flow characteristics, distribution of flow velocities across the floodplain or to predict net floodplain deposition.

The hydraulic model applied in the Rivillas River simulated the 1997 flood, in which the maximum discharge was 799 $m^3 s^{-1}$ (at the confluence with its main tributary at Badajoz city). Other discharges considered along the modelled stretches (Fig. 3) were 156 $m^3 s^{-1}$ (Romera), 180 $m^3 s^{-1}$ (Cansini), and 300 $m^3 s^{-1}$ (Galache) (Ortega and Garzon, 2009).

In the case of the Azohía Rambla we did not start from a specific flood but tried to estimate the possible effects of recent anthropogenic changes on design floods models. To that end we run hydraulic models in three possible scenarios: small-magnitude floods that mainly affect the channel (1.5-year return period) and extraordinary floods with 100 and 500-year return periods – thresholds considered in the Spanish Water Act for flood hazard mapping. Peak discharges considered were 7 $m^3 s^{-1}$ (1.5-year return period), 55 $m^3 s^{-1}$ (for a 100-year return period) and 97 $m^3 s^{-1}$ (for a 500-year return period).

3.4 Significant peak flow parameters

After modelling, most suitable variables were selected to show differences in the hydraulic behaviour of the river. Not all variables seem to reflect clearly fluvial dynamics during flash-flood episodes, so we selected only those that appear to reflect changes better than others. These changes may be natural widening or narrowing, obstacles to the flow or alterations in the longitudinal slope, among others. They may also be the result of anthropogenic constrictions caused by fences, roads or bridges, channel straightening, reduction of sinuosity, or changes in roughness caused by deforestation. All these changes alter certain hydraulic parameters and can serve as indicators of the potential change of an ephemeral river after a flood. The selected variables are specific stream power, shear stress, flow velocity, water depth and water flow width / depth ratio.

Several authors have dealt with the subject of trying to relate sedimentary features to flow parameters, for instance seminal papers from Leeder (1982) and Miall (1996). Southard (1975) established relationships between water depth and bedforms. Dalrymple et al. (1978) and Southard (1975) linked features to flow velocity, and Ashley (1990) to mean sediment size. Shear stress (τ) is defined as the unit force exerted by the flow on the bottom and is similar to channel bed friction acting in a flow per longitude unit. This cannot be determined either empirically or directly for the moment (Dyer and Soulsby, 1988; De Vries, 2002). The shear stress is an extremely important value because it controls the sediment movement (Allen, 1983; Leeder, 1982; Bridge and Bennet, 1992).

Stream power represents the rate of energy expenditure at a particular point in a river system and is inherently linked to the ability of the stream to perform geomorphic work. Costa and O'Connor (1995) established relationships between stream power and incision or degradation, and other studies have addressed geomorphic changes and effectiveness, channel stability and planform, and especially channel sensitivity to high-magnitude flood events (Bagnold, 1966; Magilligan, 1992; Costa and O'Connor, 1995; Reinfelds et al., 2004). Most studies relating stream power to channel processes have favoured exploring such relationships with specific stream power, which provides a measure of the rate of energy expenditure per unit area of channel bed (Reinfelds et al., 2004).

4 Results

4.1 Recent human impacts and changes in the fluvial system

Human activity in the two surveyed areas has been of varying intensity, particularly high in the Rivillas Basin because of pressure from intensive agriculture and urbanization. No dams have been built in either the Rivillas or the Azohía watersheds, and thus both preserve an unregulated flood regime. Human impacts affect only morphological elements and land uses.

4.1.1 Changes in the Rivillas Basin prior to the 1997 flood

There are records of active human occupation in this area since Roman times, but until modern times the impact on the landscape was not very intense. The Rivillas watershed suffered several historical floods that affected the town of Badajoz downstream, but it is not until the historic flood of 1963 that we find express mention of flooding affecting the middle and upper basin. Since then there have been a number of flash-flood events related to the Rivillas, the most destructive of them in 1997.

Several changes, either directly or indirectly induced by human activity, have been identified in the basin by means of comparison with aerial photographs prior to the 1997 flood: (i) land use changes at the watershed (agricultural), (ii) morphological changes in channels and floodplain (agricultural, infrastructures), and (iii) urbanization.

The land use changes in the basin consist mainly of removal of the original vegetation cover and changes of traditional crop types (Fig. 4). The conversion of oak open-forest pastureland into vineyards and olive groves triggered accelerated erosion, especially on hillslopes, favouring intensive soil removal. Comparison of aerial photographs has revealed that changes were particularly dramatic in the years prior to the 1997 flood. Forested cover diminished from around 46 % of the total in 1956 to 25 % in 1983, while the cultivated areas increased from ∼ 53 % in 1956 to 73 % in 1983. Both land use types remained stable after the 1997 flood or decreased up to the present-day in favour of urban use (0.6 % in 1956, 1.2 % in 1983 and 5 % of total basin area in 2011).

The effects of anthropic activity in relation to the riparian domain are drainage disruption, channel realignment with meander obliteration, removal of riparian vegetation, ploughing parallel to the direction of flow and inappropriate farming practices (Ortega and Garzón, 2009). There was widespread channelization, causing narrowing and straightening. Thus, the river's sinuosity was reduced from 1.32 to 1.07 in the upper reach and from 1.14 to 1.04 in the lower Galache reach (in fact *galacho* is an old Spanish word for "meander").

4.1.2 Changes in the Rivillas system after the 1997 flood

The most striking changes on the Rivillas River, however, reflect the extraordinary scale of the 1997 flood damage as a result of the increase in bedload induced by anthropic changes upstream. After the flood, the result of these changes in erosion-deposition effects on the floodplain was dramatic. There was observable scouring on the floodplain and channel, further aggravated by inappropriate farming practices such as deep ploughing parallel to the main direction of flow. Locally, up to 40 cm of the upper soil layer was detached as a blanket and removed in the form of soft pebbles. Note that according to Poesen and Hooke (1997), tillage erosion increases as a result of deep ploughing. The entrainment of

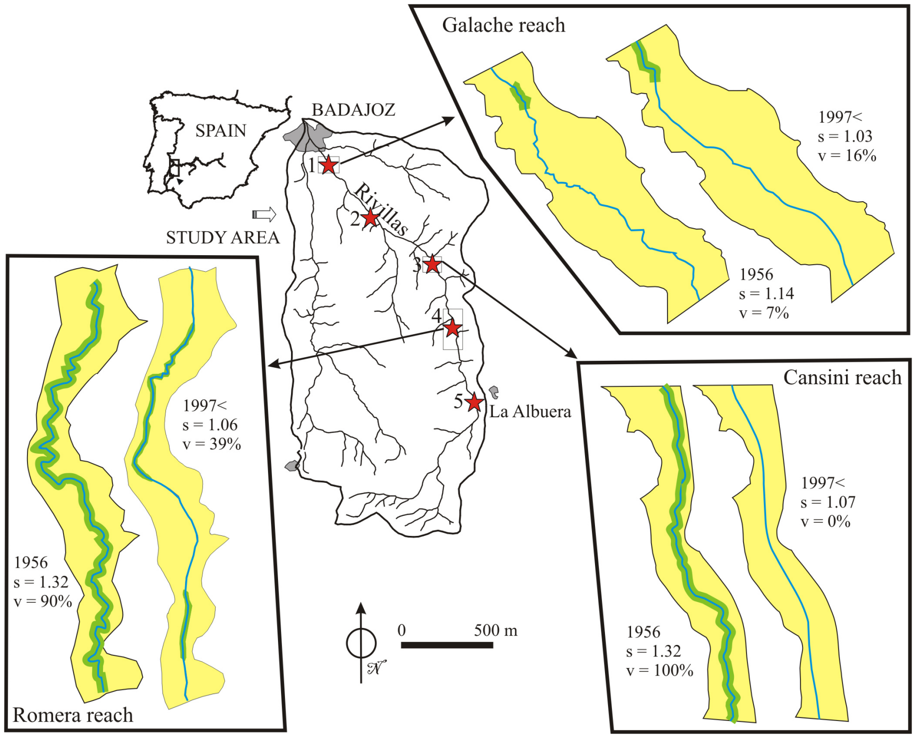

Fig. 4. Situation of the studied reaches in Rivillas River (red stars): Galache (1), Acuapark (2), Cansini (3), Romera (4) and Huerta Peña (5). Changes between 1956 and 1997 in channel sinuosity (v) and riparian vegetation (v) in three selected sites on the Rivillas watershed is shown.

large amounts of sediment into the fluvial system led to the build-up of alluvial fans on the floodplain in the early stages of the flood event, which were afterwards washed out by the flood. In some cases the strong floodplain erosion even forced the recovery of earlier channels as stream velocity and local incision power increased.

The removal of riparian vegetation diminished channel and alluvial plain flow resistance, also favouring erosion. However, where there had been unrestrained riparian vegetation growth on the stream banks due to the abandonment of pastures, channels became constricted and flow capacity was reduced.

Much research has been done on the influence of riparian vegetation, as it affects the available energy on the channel. Reaches with more riparian vegetation show less erosion than deforested reaches. As reported by Hooke and Mant (2000), there are marked differences between vegetated and non-vegetated sections, but the role of different plant types in reducing the erosivity of flows is also a factor to consider. As Dean and Schmidt (2010) have shown, the influence of non-native riparian vegetation can be significant in the exacerbation of channel narrowing and vertical accretion processes. In our case, the excessive deposition due to riparian trapping reduced channel capacity locally and triggered overbank flow and channel diversion.

Urbanization mainly affected the lower basin where urban expansion had taken place, but there were also many isolated buildings in the middle of the floodplain further upstream (aerial photographs, Fig. 4). Man-made structures such as causeways, bridges, roads and buildings also limited the flow capacity of the channel and floodplain. One important factor affecting the energy balance in the channel is constriction and modification of the river course, so that the flood water flow is different from the normal pattern of overbank flow and sluggishness over the floodplain. In this case, under flood conditions the alluvial plain performed the function of a high-velocity flow channel in a semi-confined environment.

4.1.3 Recent changes in the Azohía Basin

Transformation of the land by human activity was intense on the Mediterranean coast as early as the Bronze Age, and especially in Roman and Arab times, with large-scale water transfer and irrigation works (Hooke, 2006). Traditional agriculture transformed the landscape, with building of agricultural terraces for dryland cereals, almond and olives trees, but there was an intense transformation especially starting in the early 20th century (Conacher and Sala, 1998; Hooke, 2006). In recent times, these crops have been partially abandoned in the upper and lower Azohía watershed. The Azohía fan, however, has been partly urbanized, bulldozed and flattened, except for the main active channel.

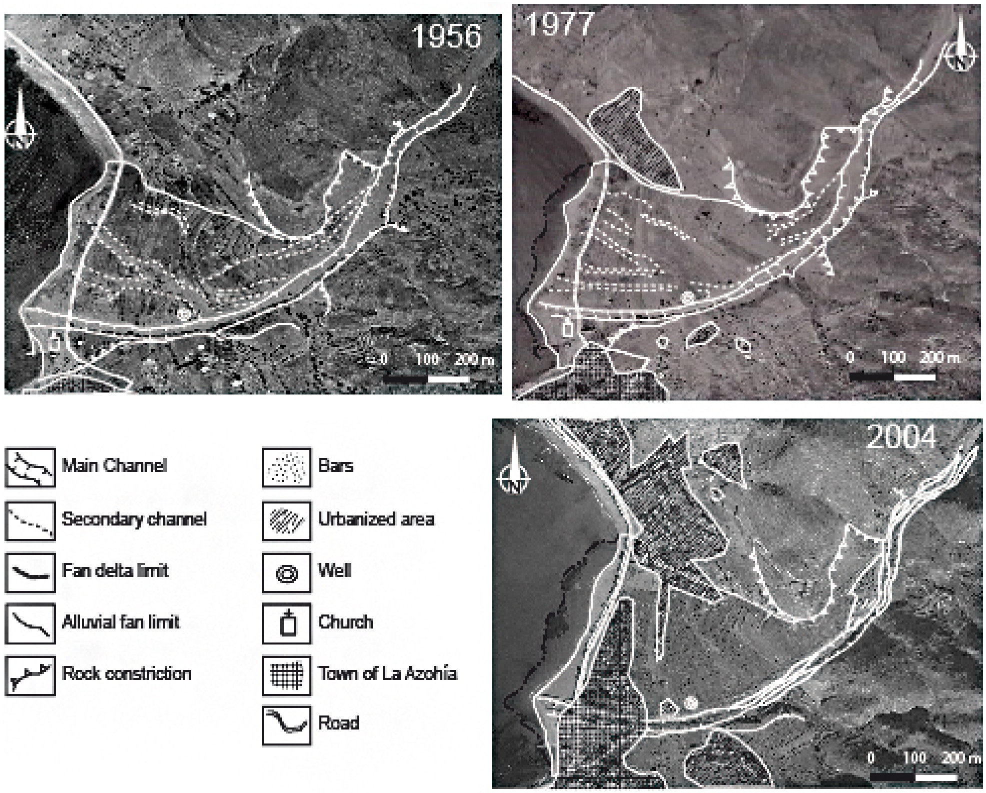

Fig. 5. Aerial photograph comparison in the Azohía alluvial fan between 1956, 1977 and 2004.

The Azohía area is scarce in historical records of flood activity and human-induced changes. Only by comparing aerial photos have we been able to establish recent morphological changes in the area (Fig. 5). In the first available photographs, from 1956, there are signs of recent flood-reworking activity in the stream, probably due to extreme flooding in the Iberian Peninsula in 1947. There are evident primary and secondary channels at many points, and zones of recent avulsion. The alluvial fan seems still to be functional throughout. A few years later, in the 1977 pictures, we observe that the main channel is still very active, possibly following another high-magnitude event in 1973 which affected many catchments throughout the region (López-Bermúdez et al., 1979). In that year there were still traces of secondary channels and avulsions and the main channel had widened.

The most important fan changes, however, are more recent. From 2002 to 2009 there was increased entrenchment in the active channel, causing narrowing and constriction. Channel width has decreased from 42 to 20 m in the last 63 years (1956–2009), largely as a result of expansion of the urbanized area in the same period, from 2 to 44.5 km^2 (Fig. 6). In addition, longitudinal profile changes in channel width are concentrated in widenings and open sections; very few occur in constrictions, and there are practically none in the lower part of the stream due to artificial channelization (post-1981). Morphologically, there are no traces of secondary channels, and there is no evidence of reworking on the alluvial fan surface. The fact that all activity is concentrated in the main channel may indicate a reduction of stream activity, which would mean less sediment build-up in the fan area.

4.2 River response to flood events

4.2.1 Post-flood analysis on the Rivillas River

In 1997 an extremely destructive flood occurred in the Rivillas stream affecting the town of Badajoz. The flood caused 23 deaths and material losses estimated at USD 150 M. During the period 5–6 November, a highly active front crossed the Iberian Peninsula in a SW–NE direction, producing heavy rainfall that reached historic maxima at almost every rain gauge station in the area and equalling or exceeding the 500-year return period. A mesoscale convective storm (MCS) released 120 mm of rain over the entire basin, and a significant part of the rain fell in 1 h. Moreover, all nearby rivers in Spain and Portugal produced floods with catastrophic results in terms of human and material losses. Preceding rainfall was also heavy, exceeding 84 mm in the previous 3 days. The confluence of the large Calamon tributary stream in the lower part of the Rivillas Basin within the built-up area produced a very rapid rise in the floodwaters (Figs. 7 and 8b).

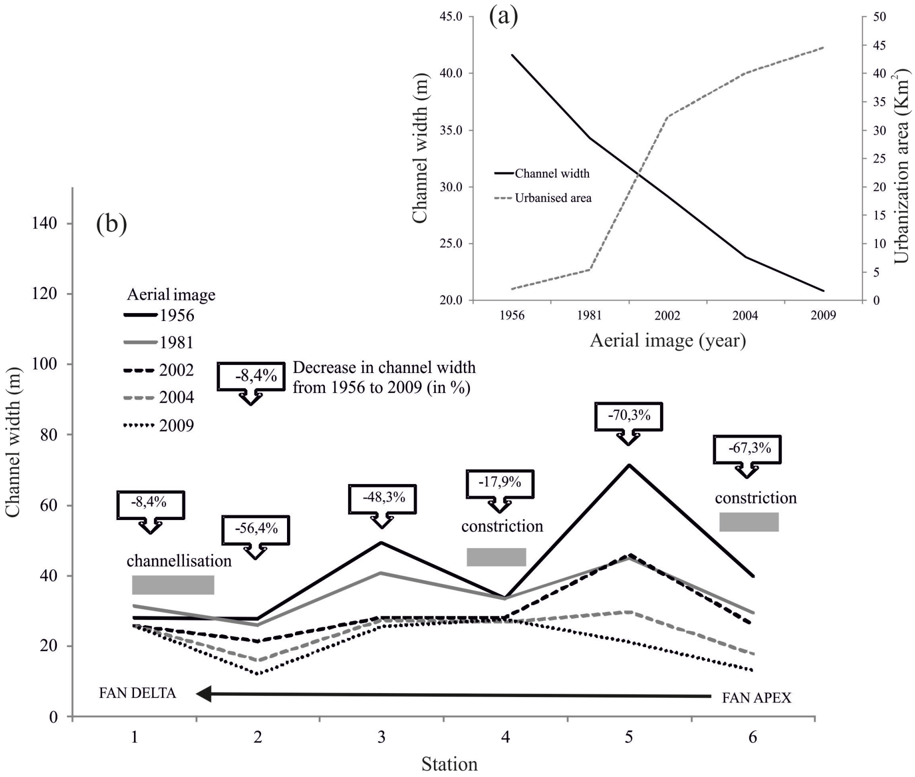

Fig. 6. Human-induced changes in the Azohía fan from 1956 to 2009. **(a)** Changes in channel width compared to urbanized area, **(b)** decrease in channel width (%) from fan apex to fan delta.

There was a lag of barely 2 h between rainfall and flood peak in Badajoz. The scale of the disaster was also favoured by the false sense of security induced by the stream channelization within the town.

The severity of the consequences was determined by the flashiness of the flood event and the change of land use on the floodplain (Fig. 8). In fact, there had been a shift towards intensive farming in the watershed and the active channel had been channelized through a built-up area, thus favouring human occupation of the banks (Ortega and Garzon, 2009).

Maps have been generated for five river sections (location on Fig. 3) based on a detailed cartographical survey a few days after the event, showing the anthropic modifications and surface erosion and sedimentation (Fig. 9). The results are summarized in Table 1, showing that there is no clear erosive-depositional distribution from the upper reach (Huerta Peña) to the downstream one (Galache). The percentage of eroded surface differs from one reach to another depending on the degree of human alteration and is concentrated particularly in those sections where the transformation has been most intense. We note that the scale of erosion in relation to total flooded area is greater in more anthropized reaches, like the Acuapark (41 %) and Cansini (48 %) reaches. In the other three reaches, erosion affects between 20 and 37 % of the total flooded area. There is no downstream gradation along the basin, and erosion seems rather to be related to changes in the original sinuosity and the amount of remaining riparian forest.

There is likewise no distinctive pattern of sedimentation. This is still very low in the lower reach (Galache) and very high in the medium-high Romera reach, and seems to correlate more with fan and tributary contribution areas. Also, the area unaffected by erosion or sedimentation processes is smallest in the two more-anthropized sections.

In order to better understand the origin of these effects, three sections have been selected for hydraulic modelling and the stream power has been calculated. These are in the upper-middle part of the basin (Romera), the middle, heavily colonized reach (Cansini) and the lower part of the basin (Galache). Figure 10 shows the stream power together with areas where erosion has been intense and plots major anthropic modifications capable of generating changes in river behaviour during the flood.

There is a relationship between anthropogenic changes in the floodplain and increased stream power. This usually occurs downstream of the disturbance and the intensity of erosion correlates with the curve peak, slightly displaced downstream. Some elements, such as roads, crossings or tracks have a direct and immediate effect (Fig. 8f and g). In other cases the increase of stream power is gradual, as in instances of lateral road constriction (Figs. 8e and 10a) which confines the river and generates localized erosion. Of all the modelled

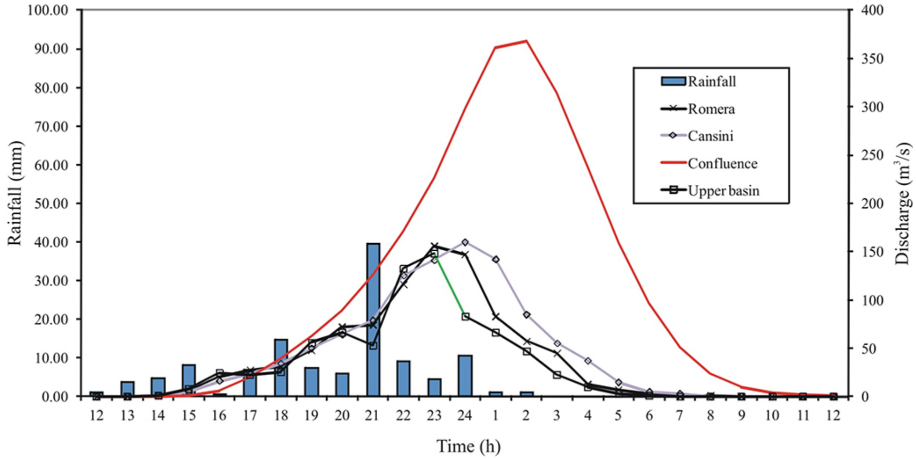

Fig. 7. Rainfall distribution and hydrograph of the 1997 flood event for the upper, medium (Romera and Cansini reach) and lower reaches (Confluence) at the Rivillas Basin

Table 1. Rate of erosion, sedimentation and areas free of changes in relation to flooded area in five selected reaches along the Rivillas Basin. All units in km^2, in parentheses comparative percentage of the entire reach area.

	Reach				
	Galache	Acuapark	Cansini	Romera	Huerta Peña
Erosion	0.086 (31.5 %)	0.080 (41.0 %)	0.079 (48.2 %)	0.034 (20.5 %)	0.029 (37.5 %)
Sedimentation	0.030 (11.2 %)	0.049 (25.1 %)	0.039 (24.2 %)	0.069 (40.9 %)	0.017 (21.8 %)
No change	0.156 (57.2 %)	0.025 (12.8 %)	0.046 (27.26 %)	0.066 (38.5 %)	0.034 (41.3 %)
Total flooded area (km^2)	0.272 (100 %)	0.195 (100 %)	0.164 (100 %)	0.169 (100 %)	0.078 (100 %)

human modifications, artificial straightening or channelization do not immediately cause increased erosion, even if the stream power increases, but erosive features usually appear some tens of metres downstream from the starting point of the channelization (Fig. 10a and c).

4.2.2 Pre-flood analysis (the Azohía Rambla)

The modelling of the Azohía Rambla was done under present conditions, with no significant flood occurrence in the last few years. The results, however, reveal some anomalies with respect to the fluvial dynamics and channel configuration to be expected in an ephemeral channel. This anomalous situation implies a lack of channel adjustment to future possible flow conditions, and hence the possibility of weak alluvial reaches, where abrupt channel changes could be expected if the 1.5-year discharge is exceeded. This approach can provide the key to predicting future responses and likely changes in the Azohía Rambla.

Morphologically, this ephemeral system combines a confined reach upstream (Rambla type channel) and an open distributary system downstream (alluvial fan). This configuration has been modelled for three flood scenarios: the 1.5, 100 and 500-year return period floods. We have studied the behaviour of hydraulic parameters such as top water width (Fig. 11a), shear stress (Fig. 11b) and stream power (Fig. 11c), and also cross-relationships like width vs. depth (Fig. 11d), velocity vs. width (Fig. 11e) and vs. depth (Fig. 11f).

Figure 11a shows how along the longitudinal profile, the flow width changes from low to high discharges (medium- and high-magnitude floods). As one might expect, in the upper reaches considered here the water width does not vary significantly between low discharge and high-magnitude floods due to channel confinement between valley slopes. However, where the valley-confined channel ends and the distributary fan begins there is a large increase of water width for the medium- and high-discharge scenarios as a result of water spreadout. This obviously implies greater energy in the confined channel reach and in the resulting morphological features associated with it.

We have considered the behaviour of hydraulic parameters such as shear stress and stream power over the longitudinal profile in relation to energy distribution. In Fig. 11b we observe that shear stress values are higher upstream in the confined area, but there are abrupt changes associated with

Fig. 8. Pictures of the Rivillas flood. **(a)** Slope erosion and fans developed in recently introduced vineyards, **(b)** Rivillas and Calamon Rivers confluence in Badajoz city, **(c)** anthropic flow limitations in floodplain secondary channels (Acuapark reach), **(d)** natural overbank sedimentation favoured by riparian vegetation (Romera reach), **(e)** anthropic disturbances due to longitudinal road near the channel (Romera reach), **(f)** perpendicular track and effects downstream, **(g)** soil upper profile dismantling showing scours along deep plough marks (Romera reach).

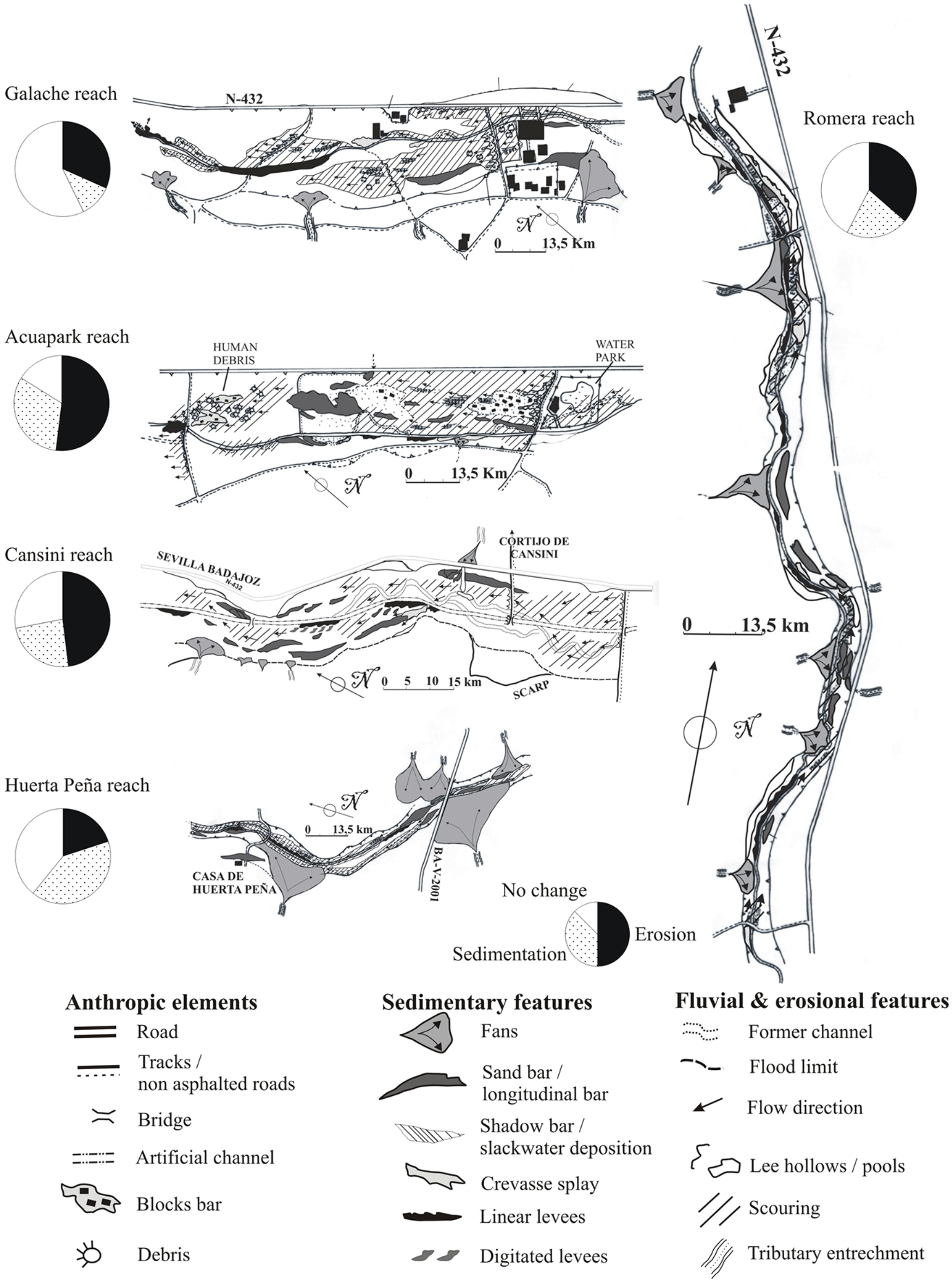

Fig. 9. Distribution of erosion and sedimentation features along selected reaches and anthropogenic disturbances on the floodplain in the Rivillas River. See Fig. 2 for location.

different morphological configurations, essentially valley narrowing and widening. There is an increase of shear stress from low discharge to the medium- and high-magnitude flood scenarios. As expected, shear stress decreases in the fan area with loss of transport capability and prevailing deposition, except for the low discharge scenario, which denotes a slight increase of energy and sediment transport capacity in the main channel due to channel entrenchment. Figure 10c shows that distribution of stream power is similar to shear stress, with energy peaks located in valley contractions and expansions. There is more energy in the confined channel than in the fan due to the steeper gradient, less roughness due to confinement and cross-section changes controlled by bedrock outcrops. At the fan apex, there is a sharp drop in stream power, except in the main channel where there is a slight increase at the lower end. This parameter again shows

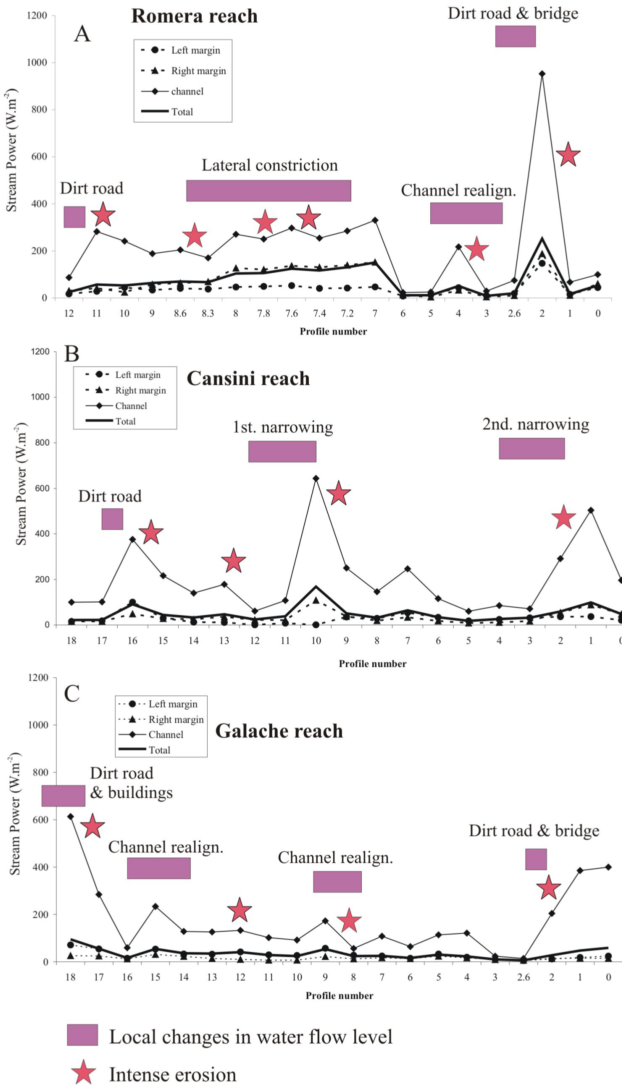

Fig. 10. Influences in stream power values of three selected reaches from upstream to downstream in Rivillas River: Romera **(a)**, Cansini **(b)** and Galache **(c)**. Human disturbances and intense erosion sites are located in the longitudinal profiles

a normal distribution of energy in confined and non-confined sections and with low and high discharges, except in the lowest profiles where energy increases slightly during low discharge.

The variables analysed in cross-diagrams (Fig. 11d–f) indicate the relationships between channel morphology, width and depth, and flow velocity. In Fig. 11d the ratio of channel width versus flow depth increases from upstream to downstream, with water width increasing downstream, slightly in the confined reach, and conspicuously in the fan area. The only exception occurs on the fan reaches in the low discharge scenario where the trend is the opposite, suggesting a change of channel morphology.

If we consider velocity in relation to channel depth and width (Fig. 11e, f), the velocity generally decreases from upstream to downstream as width increases (Fig. 11e) and hence there is also less water friction on the bed bottom. This is especially noticeable in the fan area where the overflow and the friction surface area are greater for the medium- and high scenarios. The trend is opposite, however, at the low discharge stage where there is an increase in velocity downstream due to diminishing channel width and roughness.

Again we find a similar tendency if we look at velocity in relation to channel depth (Fig. 11f). In medium- and high-discharge scenarios, water depth decreases from the upper to the lower reaches and from the confined reaches to the fan. This is especially clear in the fan, where the decrease of depth is greater and there is channel overflowing. Again there is an opposite trend during low discharge where the depth and velocity increase.

In a normal context, rock-confined ephemeral streams of this kind developing into a fan would suggest a downstream decrease of flow velocity due to the diminishing slope and widening and deepening of the channel. In our case this was the pattern we observed for medium- and high-flow modelling. But for the low-flow scenario, we found more energetic conditions than would normally be expected, indicating a major anomaly that was only found for the lowest channel profiles near Azohía village.

Briefly then, all the studied variables suggest that the behaviour of the rambla-fan system is normal in the three selected scenarios, except for the downstream channel reach, where the response is anomalous. The currently observable lower reach entrenchment and the consequences that may be expected from such a misfit in channel configuration are discussed below in the general context.

5 Discussion

Both the cases considered here represent examples of the response to human interference in the river system. Although the main cause of local damage has been identified as construction works such as roads and channel straightening, other widespread basin changes need to be taken into consideration in order to understand such significant changes in stream dynamics. As a whole, in both cases the situation can be expressed in terms of the relationship between water discharge and load availability in the channels, forcing either erosion or deposition. Erosion vs. deposition is a balance that can be very much influenced by environmental factors, causing sediment deficit or sediment excess (Lane, 1955; Schumm, 1977).

The relationship between anthropogenic changes in the floodplain and increased stream power is clear in the Rivillas and Azohía streams. Both systems belong to similar Mediterranean climatic environments although with slight variations. The river systems developed by each of the analysed

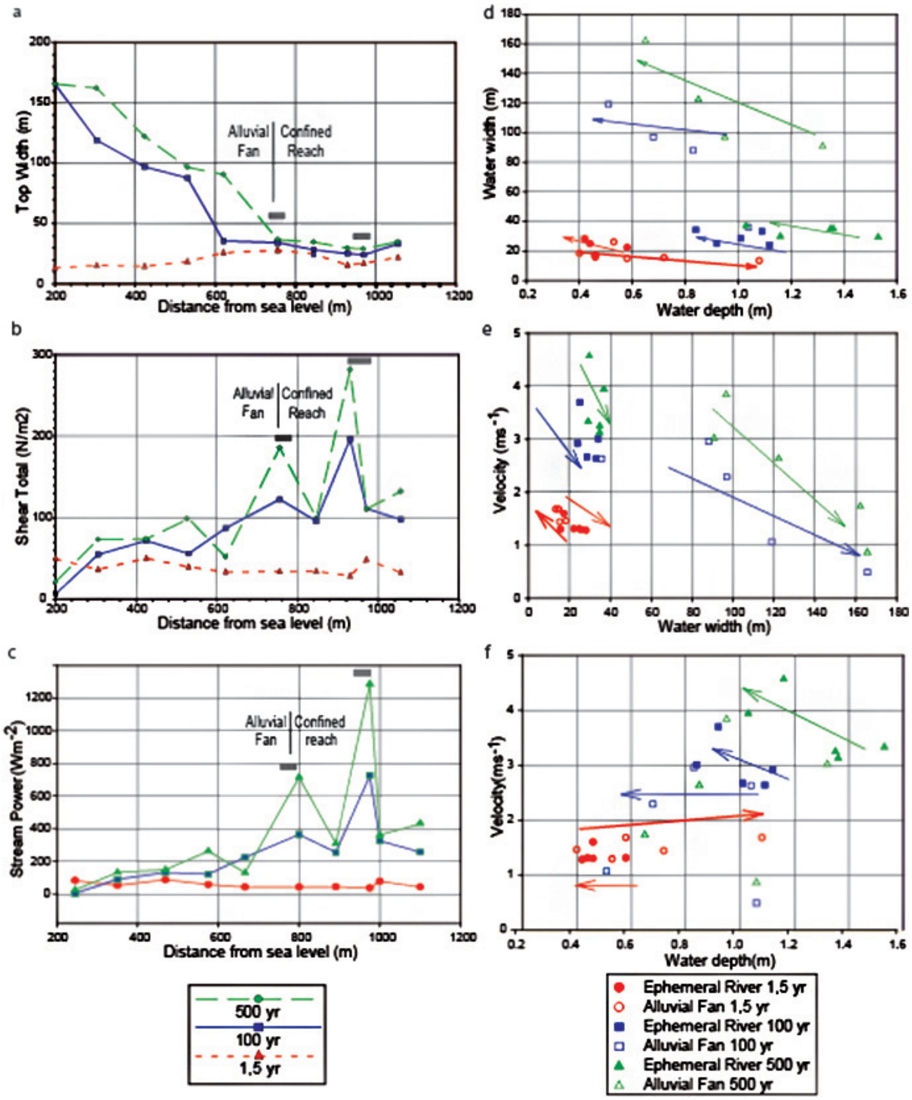

Fig. 11. Results of selected variables in the Azohía Rambla in the three considered scenarios. **(a)** Flow width changes in longitudinal profile, **(b)** water width / depth ratio, **(c)** water depth in relation to flow velocity in channel, **(d)** water width in relation to flow velocity in channel, **(e)** adimensional shear stress in longitudinal profile, **(f)** stream power in longitudinal profile. Grey blocks indicate natural narrowings.

streams differ morphologically. Differences between the two case studies are attributable more to environmental factors than to regional climatic variability. The Rivillas stream runs through a basin with preserved open-range pastureland and climax vegetation that protects the soil during the long drought months and renews its grass cover before the heavy autumn/winter rains. Azohía is characterized by a receding vegetation catchment and fast-growing urbanization at the mouth, with high-intensity convective rainfall after the dry season, where there is little resistance to erosion.

Rivillas was once a well-organized fluvial system with a well-defined medium sinuosity channel migrating on to a gentle valley floor. Azohía was more torrential in character, with a narrow valley transfer channel and an alluvial fan at the relief outlet. Studies in both cases demonstrate how the alterations in the basin since the 1950s (first aerial photos) modify the dynamics of the channels. The common factor affecting both basins is the modification of load/discharge ratios, as load supply has been significantly transformed.

In the Rivillas case, there has been a significant increase in load availability on the basin due to pastureland removal and a shift to intensive agriculture during recent decades. Our study evaluates the response of the system in relation to the post-flood channel geometry and deposit dynamics. High erosion rates on the catchment lead to excessive load supply in a narrowed channel due to artificial straightening and uncontrolled riparian vegetation growth. Moreover, secondary flood channels had disappeared in most cases, due either to the reworking and filling for agricultural purposes or to urban construction in the riverbed. The loss of former channel efficiency in water evacuation and the increased load discharge induced generalized overbank flooding during the 1997 event and the whole valley floor acted as a high-energy floodway. The river transformed from a single medium-sinuosity channel to a wide and shallow-braided stream that had lost its original sinuosity. Deposition was associated with local erosional sources and tributaries delivering new sediments to the main channel by means of lateral fan development. Stream power increased gradually through lateral road constrictions, unlike at small bridges or crossings where the downstream effect is immediate. The change in channel pattern conditions with adjustment in stream morphological parameters (width, depth and gradient) increases the energy balance during flood events, thus generating riverbed destabilization and raising flow velocity and removal capacity and increasing the risk of future floods.

The question arises whether the changes in channel morphology are due to the occurrence of a single medium- to high-magnitude event or stem from land use transformations.

The natural Rivillas channel had previously been straightened, narrowed and constricted by artificial levees and vegetation. This loss of efficiency, together with occasional but intense load supply contributions from tributaries, enhanced the effect, whereby the entire floodplain reacted as a wide, shallow channel with deposition of bed bars, tending more to a braiding pattern response. This was a large flood, but basin conditions were also extremely perturbed. Adjustments during the 1997 flood have been significant with a major geomorphic impact, probably because the stream was in metastable equilibrium due to new basin conditions.

In the Azohía fan approach, the results show that there is a tendency for the flow to be concentrated in a deep, narrow channel. We do not have specific data on when this entrenchment began or its causes. It is clear that within fan dynamics dispersive streams may be transformed into incised channels due to intrinsic geomorphic evolution when they exceed a slope threshold, without having to invoke other extrinsic reasons (Schumm, 1977). But that is not the case here and there is no over-steep fan with excess gradient to force rejuvenation and entrenchment.

Therefore other extrinsic geomorphic thresholds should be considered to account for this adjustment, such as tectonics, climate, land use changes or anthropogenic interference. This situation could be due to an overall tendency to incision in several Mediterranean rivers as described by Garzón and Alonso (2002), Liebault and Piegay (2002), Uribelarrea et al. (2003) and Hooke (2006). These refer to a present tendency towards entrenchment and confinement in the channel domain, accompanied by reduced deposition in floodplain areas, probably due to river adjustment following the excessive sediment build-up derived from the 19th-century (Late Little Ice Age) increase of flooding. Such a climatic response, however, tends to be associated more with large permanent rivers than with ephemeral streams on distributary alluvial systems like the one described here.

Considering other possible extrinsic geomorphic thresholds, Mather and Harvey (2008) have suggested that tectonics combined with sea level changes could be responsible for changes in nearby ephemeral rivers. However, these changes would not be applicable to our timescale based on 50-year aerial images. There has been no check dam construction or reforestation (other suggested causes of extended stream narrowing) in the Azohía watershed, and these could only explain some local entrenchments.

The transformation from a wide, shallow channel pattern to a single entrenched channel can be better explained as the result of reduced load availability. This implies flow convergence into a channel that has become deeper and narrower. There are other aspects that also suggest a loss of load supply. Recent abandonment of agricultural land in alluvial catchments has prompted an increase of shrub and open forest vegetation. Although this does not provide dense soil protection, it is better cover than the previous olive, almond and vine plantations. As observed by Hooke (2006) for SE Spain and other Mediterranean areas, this transformation has reversed stream processes, reducing sediment load contribution to channels.

Various protection works have been carried out in the fan area that also help to convey the water flow into one single channel. Longitudinal defences, roads and protection walls also assist water convergence into the main channel. Bed reworking in the mouth of the main channel has been undertaken to drain more water during flooding. These transformations have removed some sediment, causing upstream propagation of incision in the main channel, which is becoming eroded and entrenched.

In brief, the stream dynamics in the Azohía case are the reverse of those in the Rivillas case, but the ultimate explanation may also lie in an alteration in channel load supply conditions. According to Schumm (1977), a channel load increase produces an increase of channel slope and width and a decrease of depth and sinuosity. Such is the case of the Rivillas stream, which developed a braiding pattern during the flood.

On the other hand, loss of sediment supply in the Azohía watershed will induce diminishing width and a depth increase prompted by hungry waters (Kondolf, 1997). Such entrenchment increases water velocity, which in reaction drives slope reduction and triggers upstream propagation of incision. This feedback mechanism of upstream scouring also forces bank undercutting with landsliding that will tend to refill the channel and stabilize the entrenched channel banks, unless they are protected by riparian vegetation. Hydraulic modelling shows that narrowing and deepening of the channel is related to low flood episodes; modelling of high-magnitude floods offers a contrary pattern in width-to-depth ratios, so that the stream probably acquires new sediment from banks and lateral fans, resulting in enlargement and shallowing of the channel.

Such channel metamorphosis would match the expected morphological response proposed by Schumm (1969) for a lack of load situation that consists of increasing depth and sinuosity and diminishing width and depth. New insights into Lane's relationship, proposed by Dust and Wohl (2012), expand Lane's conceptual model to better visualize the complex river response. Load disturbance will introduce not only changes in slope, but also a cross-sectional adjustment. This approach may contribute a new perspective to further discussion (Huang et al., 2014).

There are two key aspects, closely linked, that require deeper investigation: (i) the specific nature of ephemeral channels, which introduce a different notion of river equilibrium and (ii) the significance of human-induced changes on the watershed that remain dormant and may consequently alter river dynamics. The nature of these ephemeral streams that combines long-lasting time lags with low river activity but intense human perturbation, defines a metastable equilibrium with geomorphic changes occurring only in a context of medium- to high floods.

The capacity of humans to transform river systems in recent times cannot be ignored. Proposals to consider a new Anthropocene Era have recently been debated since anthropogenic processes may have significant and long-lasting consequences (Zalasiewicz et al., 2013). As Wohl (2013) proposes, understanding the historical context and our capacity to predict responses might be a challenge to test our scientific environmental comprehension.

6 Conclusions

Modifications occurring in two basins since the first available aerial photos (1950s) and changes in their channel dynamics have been analysed and compared, so that conclusions can be drawn about channel readjustments and the capacity of systems to respond appropriately to the different environmental conditions that cause channel instability.

Lane's relationship is useful as a conceptual model that allows us to understand complex river responses involving adjustments in river geometry. The relationship between human-induced load supply changes in the fluvial system and increased stream power is clear in the Rivillas and Azohía streams. Bedload changes modify the stream's morphological parameters, inducing changes in river patterns and initiating a period of instability until the river readjusts to the new supply conditions.

From a hydraulic study of a high-magnitude flood event on the Rivillas River, it has been possible to detect changes in morphological stream parameters. The causes of the destabilization of a formerly sinuous channel and the shift during the flood towards a braided pattern appear to be related to a load increase due to intensive land use transformation.

The situation in the Azohía Rambla can also be explained by an alteration in channel load supply conditions, but in an opposite sense to the Rivillas case. The Azohía stream apparently presents little activity, but the channel indicates active entrenchment on its lower stretch. This fact, together with data provided by aerial photos, suggests that anthropic pressure on the watershed is now diminishing, with abandonment of crop farming in the basin headwaters but increasing urbanization on the coastal fringe.

The loss of load supply in the basin induces entrenchment and narrowing in the fan and triggers a feedback reaction that will favour upstream incision. In these conditions of diminished supply, the system dynamics have become unstable; this increases water speed, upstream scouring and bank undercutting, driving a destabilizing response mechanism.

Although starting conditions are different in both ephemeral streams, in the after-flood analysis, we deduced that hydraulic modelling can supply an insight into how critical points will react during a flood. As a consequence, in the case of the Azohía stream, we can interpret the presence of anomalous critical points from the results of the hydraulic modelling. Changes in channel and planform morphology can therefore be analysed in studies before a flood event occurs (modelled response case) in order to predict analogies to those found after a real event (observed response case).

The main limitation of the hydraulic zoning approach is that channel morphology is subject to trigger latent changes during floods. Given that this is the official method in use, we need to have a better understanding of the significance of anomalous points. Most importantly, however it helps to demonstrate that hydraulic modelling of present channel conditions may depict a scenario inducing a false sense of security, as basin changes and modified channel conditions may mask actual flood results.

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