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

J. A. Ortega[1], **L. Razola**[2], **and G. Garzón**[3]

[1]Dpto. de Geología y Geoquímica, Facultad Ciencias, Universidad Autónoma de Madrid, Madrid, Spain
[2]School of Geography, Earth & Environmental Sciences, University of Birmingham, Birmingham, UK
[3]Dpto. Geodinamica, Facultad de Geología, Universidad Complutense de Madrid, Madrid, Spain

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Correspondence to: J. A. Ortega (j.ortega@uam.es)

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Abstract

Ephemeral streams induce flash-flood events which cause dramatic morphological changes and impacts on population, due the intermittent activity of these fluvial systems. Human pressure changes the fluvial environment and so enhances the effects of natural dynamics. Local human-induced modifications can be latent over long periods of time. These changes can be studied after the flood event, to quantify their effects and detect which are most harmful. In this paper we study flash-flood effects at two sites in Spain and compare the results before and after a flood event. Erosion is associated with areas where there have been more anthropogenic changes in floodplains and channels. Deposition is related to erosional processes in the watershed and to the tributaries. Disruption of river channel patterns changes connectivity and scouring appears due to energy excess. This excess tends to concentrate at weak points downstream produced by anthropic disturbances. Riparian vegetation is an energy sink and reaches with more cover show less erosion than those with deforestation. Infrastructures perpendicular to the direction of flow increase stream power, but peaks of erosion on the floodplain appear displaced downstream. It is important to detect human changes by analysis of hydraulic variables before the occurrence of an extraordinary event in order to anticipate catastrophic consequences resulting from inappropriate fluvial management.

1 Introduction

Ephemeral streams are less known in comparison to perennial rivers, mainly due to their location in less populated semiarid or arid environments and only sporadic activity. Therefore, there is also generally a lack of information about rainfall and discharge. A flash-flood represents an abrupt and 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 (Osborn and Lane, 1969; Sharon and Kutiel, 1986; Komuscu et al., 1998). The short but high intensity of precipitation together with its sporadic character further difficult to obtain rainfall registers that helps understanding of the hydrodynamics of flash-floods.

In many parts of the world such as Mediterranean countries, however, some of these ephemeral channels affect urban areas. Dedkov and Mozzeherin (1992) suggest 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 (Bull et al., 1989; Conesa-García, 1995; Poesen and Hooke, 1997; Camarasa and Segura, 2001; Lopez-Bermudez et al., 2002), but also in other areas such as the Pyrenees (White et al., 1997; Gutierrez et al., 1998) or Extremadura (Ortega and Garzón, 2009a). Those widely-scattered areas highlight the importance of understanding flash-flood hydrodynamics in order to establish some level of prediction of sensitive areas. One method is remote sensing (Hoshi et al., 1989; Storck et al., 1998; Foody et al., 2004), which provides better information about aspects of hydrological models such as precipitation (Schick, 1988; Bull et al., 1999; Graef and Haigis, 2001; Bracken et al., 2008), infiltration (Sharon and Kutiel, 1986; Osborn and Lane, 1997; Gheith and Sultan, 2002) or losses of transmission (Goodrich et al., 1997; Mudd, 2006).

Fluvial processes in dryland rivers have been pointed out by Graf (1988) and Bull and Kirkby (2002). The geomorphic effects of flash-floods in ephemeral channels are intense since the floods are rare but have a high geomorphic potential for change, especially if the event presents a long-lasting peak discharge (Costa and O'Connor, 1995; House and Peartree, 1995; Ortega and Garzón, 2009a). A flashy flow regime means channels tending to instability and with changing morphologies (Conesa-García, 1995; Hooke and Mant, 2000). There are a variety of natural changes (Merrit and Wohl, 2003) related to storm size, presence or absence of riparian vegetation in channel (Tooth, 2000) and the effects of the vegetation type and its special location (Sandercock and Hooke, 2010, 2011), type of hydrological regime controlling peak flow, sediment transport and channel width (Osterkamp, 1980), steep gradients, coarse bedload and channel geometries that lead to highly turbulent flow (Kochel, 1988). Merrit and Wohl (2003) explain changes in channels as a result of agradational (net fill) or degradational (net scour) processes, derived from wider or confined valley reaches. These local changes suggest a wave-like movement as in pulses of more or less active areas. Similarly Ortega and Garzon (2009b) described an alternation of processes in ephemeral and confined bedrock rivers in SE Spain, but also in non-confined rivers (Ortega and Garzon, 2009a). Hooke (2003) gives the term connectivity to the physical linkage of sediment through the channel system and suggests that identification of the connectivity within a channel allows us to understand the propagation of changes and the sensitivity of disturbance response.

In this paper we compare flash-flood results at two sites. In one case there is geomorphological and hydrological information before and after flood occurrence, making it possible to identify changes in water yield, sediment supply and channel form (Fig. 1) derived from human activity (observed response). In the second case we use the methodology deduced from this kind of information for the detection of changes that might be expected and result in damage after a flash-flood event (modelled response). A detailed study of aerial photos, hydrology after a particular flood, high water marks and sedimentation-erosion processes in a reach allow us to (i) detect which human activities cause most change during and after a flood event; (ii) establish zoning in the floodplain on the basis of this change; and (iii) use this information prior to a flood event in management and urban planning.

We selected two areas, both in small scale basins affected by flash-flood events (Fig. 2). The first is in the Rivillas River (Extremadura, Spain), where a high-magnitude flood occurred in 1997. Multidisciplinary studies have been done, including sedimentology of post flood features, geomorphology, hydrology and hydraulic modelling of the flood event. We choose as the second one an ephemeral stream with a low historical anthropic pressure, but with recent human changes in order to point out how these changes could affect stream morphology or hydrolocical pattern. This second stream is an ephemeral Mediterranean channel, locally defined as “rambla”, name that has

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been used in the scientific literature referring to an ephemeral gravel-bed stream hydrologically dependent on rainfall (Camarasa and Segura, 2001). The Azohía Rambla (Murcia, Spain), the second basin studied, is a little-known stream for which we have littleinformation about historical floods due to geographical isolation and only with little human affection until mid 20th century. A similar study as the Rivillas one was conducted on this river but prior to any flood event. Our goal is to try to detect changes in channel hydraulic parameters that may originated hazards in a future flood.

2 Study area

2.1 The Rivillas river

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 $\mathrm{mm\,yr^{-1}}$. The Rivillas River has a basin of 314 $\mathrm{km^2}$ and an average gradient of 0.0075 $\mathrm{m\,m^{-1}}$ with a main tributary (Calamon stream) similar in size and length to the main river, so that the peak discharge tends to occur at the same time at their confluence in the Badajoz urban area, where high hazard and exposure are combined.

Geologically, the Rivillas basin is composed basically of fine-grained Tertiary detritical sediments. Only the headwaters present outcrops of metamorphic limestones and shales (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, and in many cases a roughly-defined fluvial network. Some morphometric aspects in the Rivillas watershed suggest a predisposition to magnify the effects of storms.

2.2 The Azohía Rambla and alluvial fan

The Azohía Rambla and alluvial fan is located in the internal area of the Betic Range. Tectonics has played an important role in the morphological evolution of this geologically allochthonous area (Goy and Zazo, 1982; Sanz de Galdeano, 1983; Silva et al., 1992, 1994). The lithological profile of the mountains surrounding the Azohía includes limestones, dolomites, quartzites, micaschist, phyllites and diabases, but the complex and still active tectonics has induced abrupt slopes and highly disturbed and erodible materials. Within this range, tertiary basins and closed plio-quaternary valleys have developed, and that is where the Azohía Rambla and alluvial fan is located (Fig. 2). The Azohía alluvial fan is mainly composed of conglomerates and secondarily of sandstones produced by erosion of the above-mentioned materials.

The climate is semiarid with mean annual precipitation of 300 mm and a mean temperature of 18 °C. Local conditions are influenced by the barrier effect of the Betic Mountain Range.

The Azohías Rambla is 5 km long and its drainage basin measures 15 km^2. The drainage network is dendritic and elongated to the E and very asymmetric with few channels in the W area. At its mouth the Azohí a has developed an alluvial fan delta with an area of 0.22 km^2 and a perimeter of 2.3 km. The main 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 concrete walls recently builted around early 1980's.

3 Methods

3.1 Fieldwork: geomorphologic survey

An important aspect of this work is the collection of information in the field. 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. As Ortega and Garzón (2009a) have shown, fieldwork needs to be carried out as soon as possible after a flash-flood in order to describe the sedimentary features generated before they are disturbed. Post-flood

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field studies allowed us to establish a best fit in our model. 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). Another requirement is an adequate survey of High Water Marks (HWM). In calibrating the Rivillas flood hydraulic model, best field HWM data were selected eliminating these ones showing local disturbances.

In the case of the Azohía model no previous flood information was available and morpho-sedimentary 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, anthropic debris among others).

3.2 Hydraulic model

The flood model used for both sites was the Hec-ras (Hec, 1996) a one-dimensional and step-backwater program which uses the Bernoulli equation to model selected discharges (1997 flood discharge in the Rivillas and different return period discharge scenarios in the Azohía Rambla) by means of surveyed channel topography. 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.

This model has many limitations, as pointed out by Merritt and Wohl (2003), because simulated flow is one-dimensional and in many cases these ephemeral streams have multiple flow paths. Another problem is the unsteady character of flash-floods. We assumed that the error could be minimized by considering High Water Marks, which are representative of peak stages, for model calibration (Baker, 1977) and straight reaches with less error, as Merrit and Wohl (2003) assume in other ephemeral river models.

Results proved more accurate using the highly detailed HWM record of the 1997 flood in the Rivillas River.

A hydraulic model was applied in the Rivillas River area (Ortega and Garzon, 2009), simulating a particular flood (1997), in which the maximum discharge was 799 $m^3 s^{-1}$ at the confluence of the two main tributaries at Badajoz city (412 $m^3 s^{-1}$ on the Rivillas River and 387 $m^3 s^{-1}$ on the Calamón). Other discharges considered were 156 $m^3 s^{-1}$ in the Romera area (upper basin), 180 $m^3 s^{-1}$ in the Cansini reach (middle-upper basin), and 300 $m^3 s^{-1}$ in the Galache reach (lower basin near Badajoz).

In the case of the Azohía Rambla, the reverse procedure was followed. We did not start from a specific flood but sought to estimate the possible future effects associated with recent anthropogenic changes. To that end we constructed hydraulic models in three possible scenarios: small-magnitude floods that mainly affect the channel (bankfull) and extraordinary floods with return periods of 100 and 500 yr, with reference to the Spanish Water Act which considers these two thresholds for flood hazard mapping and legal considerations. The peak discharges considered are 7 $m^3 s^{-1}$ (bankfull), 55 $m^3 s^{-1}$ (for a 100 yr return period) and 97 $m^3 s^{-1}$ (for a 500 yr return period).

3.3 Significant peak flow parameters

The use of physical variables in relation to aspects of river dynamics in research on sedimentary features is not new. Several authors have dealt with the subject of trying to relate sedimentary features to flow parameters, for instance Leeder (1982) and Miall (1996). Southard (1975) and Costello and Southard (1981) tried to establish relations between water depth and bedforms. Dalrymple et al. (1978) and Southard (1975) linked features to flow velocity, and Ashley (1990) to mean sediment size. Simons et al. (1961) related features to water depth and velocity and Froude number, and Shields (1936) and Leopold et al. (1964) to shear stress. Schumm (1969) points out the significance of changes in hydrological variables for river morphology and metamorphosis, and Costa and O'Connor (1995) applied them to fluvial geomorphology to establish relationships between stream power and incision or degradation, and other studies have addressed geomorphic changes and effectiveness.

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, to channel stability and planform, and especially to 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).

The shear stress (τ) is defined as the acting force, the unitary force exerted by the flow on the bottom. This stress is similar to the force of friction of the bottom acting in a flow per unit of longitude. For the moment this cannot be determined empirically or directly (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).

After modelling, the most suitable variables were selected to show differences in the hydraulic behaviour of the river. Not all variables seem to clearly reflect fluvial dynamics during flash-flood episodes, and 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 human activity constrictions caused by fences, roads or bridges, channel straightening, reduction of sinuosity, or changes in roughness 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.

4 Results

4.1 Recent human impacts and changes in the fluvial system

One of the objectives of this work is to use the methodology described above to detect changes in river dynamics from hydraulic variables. This is applicable to areas like the Azohía Rambla where there is a lack of information. To that end this paper presents the changes identified in the Rivillas River basin after a medium-high magnitude flood event and compares it with the limited information that we have in the Azohí a Rambla. Human activity in the two surveyed areas has been of varying intensity, particularly high in the Rivillas basin because of its proximity to Badajoz city and the quality of the adjoining agricultural land. No dams have been built in either the Rivillas or the Azohía watersheds, and thus both preserve a natural flood regime. Human impacts affect only morphological elements and land uses.

As indicated by Hooke (2006), clearance of vegetation and exploitation of the land has been declining in southern Europe in recent times. This fact provides a good opportunity to compare the evolution of fluvial systems, but also to detect inherited changes in fluvial dynamics which can only be determined after a flood event in ephemeral channels, and this situation may take some time to occur.

4.1.1 Changes in the Rivillas River basin

There are records of human occupation in this area since Roman times, but until modern times the impact of this was not very intense, especially near the town, which began to expand outside the city walls from the 1940s on. The original nucleus of the city owed its foundation to the existence of a major tributary of the Guadiana, the Rivillas River (Fraile, 1995), Floods on the Rivillas River affected the city of Badajoz very little before the second half of the 20th century, since there were no houses in the potential flood area. Only a few floods have been reported historically as a result of backflow from the Guadiana to the Rivillas (Ortega, 2008). After 1940, urban areas began to encroach on the tributary channels and were therefore affected by any flooding no matter how minor. There are numerous references to damage to crops, bridges or even part of the mediaeval city walls. Structural protective measures were eventually taken, including channelization of the Rivillas and Calamon Rivers in Badajoz city. The Rivillas watershed shows changes in land use, 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 human induced changes, either direct or indirect, have been identified by means of comparison with aerial photographs prior to the 1997 flood: (i) land use changes in watershed (agricultural), (ii) morphological changes in channels and floodplain (agricultural, infrastructures), and (iii) urbanization. The most important land-use changes and damage occurred in the environs of Badajoz city. The most striking aspect, however, is the extraordinary scale of the flood damage to the city, as a result not only of the presence of buildings but also of the increase in bedload induced by anthropic changes upstream.

The land use changes in the basin consist mainly of removal of the original vegetation cover (oak trees on the hillslopes and riverine trees on the channel margins) and changes of traditional crop types (Fig. 3). Comparison of aerial photographs has revealed that changes were particularly dramatic in the years prior to the 1997 flood, and their effect on the floodplain can be observed in stream reaches showing direct anthropic influence. The conversion of “dehesa type” open-forest pasture into vineyards and olive groves triggered accelerated erosion, especially on hillslopes. This fact favoured intensive soil removal, as Poesen and Hooke (1997) also noted for Mediterranean environments. The entrainment of large amounts of sediment into the fluvial system led to the build-up of alluvial fans on the flanks of the floodplain in the early stages of the 1997 flood event, which were afterwards washed out by the flood. The effects of anthropogenic activity in the riparian domain have been reported in the Rivillas catchment by Ortega and Garzón (2009a), mainly in relation to sedimentary features developing after the flood. These changes are: drainage disruption, channel realignment (with soft margins, not cemented) with meander obliteration, deforestation of riparian vegetation, ploughing parallel to flow direction and inappropriate farming practices. Increased sediment delivery from valley side slope enhanced alluvial fan deposition on the flanks of the floodplain. 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"). The reduction in sinuosity is general, but the comparison of aerial photographs shows that there were already human modifications to the river before 1956 in the vicinity of the city (Fig. 4). This change produced local floodplain erosion, and in some cases even recovery of earlier channels as stream velocity and power increased. The removal of riparian vegetation diminished channel and alluvial plain flow resistance, 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 about the influence of vegetation. Riparian vegetation affects the available energy. Reaches with more riparian vegetation show less erosion than deforested reaches, As it has been described by Hooke and Mant (2000) that point out the marked differences between vegetated and non vegetated sections, and the role of different plant types in decreasing the erosivity of flows (Sandercock and Hooke, 2010). In some cases, however, the excess of deposition due to riparian trapping reduces channel capacity and triggers overbank flow and channel diversion.

Poesen and Hooke (1997) indicate that tillage erosion increased as a result of deep ploughing. After the Rivillas flood there was observable scouring on the floodplain and channel, produced essentially by excess flow energy, which was further enhanced by inappropriate farming practices such as deep ploughing parallel to the main direction of flow.

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. 3). Anthropic constructions 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.

4.1.2 Changes in the Azohía basin

As one of our objetives, the selection of Azohí a stream is based on the scarce historical human-induced changes and flood activity. 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 1947 flooding period in Iberian Peninsula. 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 been decreasing from 42 to 20 m in the last 63 yr (1956–2009) very much related to urbanised area increase in the same period, from 2 to 44.5 km^2 (Fig. 6). Besides, longitudinal profile changes in channel width are focused in widenings and open sections, very few occur in constrictions and are practically absent in the lower part of the channel due to chanellisation (built after 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.

Considering the coastline, it does not seem to have changed during the 1956 to 1977 period; however, comparison of this period with the recent one (after 2004) shows that the fan is eroding at its border with the sea. These demonstrates that due to urbanisation there are not enough sediment entering the system today to compensate for the erosive action of the sea, and for this reason the alluvial fan shows signs of retraction.

Transformation of the territory by human activity has been intense in 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). But not as much in this small catchment surroundings of the Azohí a Rambla, where comparison of aerial photos shows no signs of intensive occupation in the upper basin, only significative in the fan. Traditional agriculture transformed the landscape, with building of agricultural terraces for dry-land cereals, almond and olives trees, especially from the early 20th century (Conacher and Sala, 1998; Hooke, 2006). In recent times, these crops have been abandoned in the upper and lower Azohía watershed, with transition to plastic greenhouses only in areas neighbouring the alluvial fan. These new agricultural practices were not introduced in the Azohía fan itself since the area has been urbanized and partly bulldozed and flattened, except for the main active channel.

4.2 Changes in river dynamics related to human impacts

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 US$150M. During 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 yr 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 one hour. 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). 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 safety induced by the channelization of the streams.

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

Maps have been generated for five river sections (location on Fig. 3) from the detailed cartographical survey a few days after the event (Fig. 9) showing the anthropic modifications and surface erosion and sedimentation. The results are summarized in Table 1, showing that there is no clear erosive-depositional distribution from the upper (Huerta Peña) to the downstream (Galache) reach. 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 values of erosion in relation to total flooded area are higher 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 with 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 Romera medium-high 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 on the profile.

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, g). In other cases the increase of stream power is gradual, as in cases of lateral road constriction (Figs. 8e and 10a) which confines the river and generates localized erosion. Of all the modellized 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, 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 expect flow conditions and therefore the occurrence of reaches of alluvial system weakness where abrupt channel changes could be expected in case of exceeding bankfull discharge. This approach can provide the key to predictable 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 modellized for three flood scenarios: the bankfull stage and the

100 and 500 yr 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) and velocity vs width (Fig. 11e) and vs depth (Fig. 11f).

Figure 11a shows how along the longitudinal profile, the flow width changes from low discharge (bankfull scenario) to high discharges (medium and high magnitude floods). As it could be expected, in the upper reaches the water width does not vary significantly between the bankfull stage and high-magnitude floods due to channel confinement in between valley slopes. However, where the confined channel ends and the distributary fan develops there is a large increase of water width for the medium- and high-discharge scenarios as result of water spread out. This implies obviously larger energy in the confined channel reach and in the resulting morphological features associated with it.

We have considered the behaviour of the hydraulic parameters along the longitudinal profile in relation to energy distribution, such as shear stress and stream power. In Fig. 11b we observed that shear stress values are higher upstream, in the confined area, but there are abrupt changes associated with different morphological configurations, essentially valley narrowing and widening. There is an increase of shear stress from the bankfull to the medium- and high-magnitude flood scenarios. As expected, shear stress decreases in the fan area with loss in transport capability and prevailing deposition, except for the bankfull scenario, which denotes a slight increase of energy and sediment transport capacity in the main channel due to channel entrenchment. The Fig. 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 larger 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 a slight increase at its lower end can be stated. This parameter shows again a normal distribution of energy in confined and non confined sections and with low and high discharges, except in the lowest profiles where energy slightly increases during bankfull discharges.

The variables analysed in cross diagrams (Figs. 11d–f) indicate the relationships between channel morphology, width and depth, and flow velocity. In Fig. 11d the channel width versus flow depth shows an increasing ratio from upstream to downstream, water width is getting wider downstream, slightly in the confined reach, and conspicuously at the fan area. The only exception occurs on the fan reaches in the bankfull 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 therefore water friction on the bed bottom. This is especially noticeable in the fan area where overflow and the friction surface area is higher for the mediums and high scenarios. The trend is opposite, however, to the bankfull stage where there is an increase in velocity downstream due to channel width and roughness decrease.

Again we find 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 lower reaches and from the confined reaches to the fan. This is especially clear in the fan, where depth decrease is larger, by channel overflowing. Again there is an opposite trend during bankfull where the depth increases as well as velocity.

In a normal context, this type of rock confined ephemeral streams developing into a fan would suggest a downstream decrease in flow velocity, due to the slope diminishing and increasing channel width but depth decrease. This fact is observed in our case for medium and high flows modelling. But for the low flow bankfull scenario, we found more energetic conditions than would normally be expected, indicating an important anomaly that only has been found for the lowest channel profiles near the Azohía village.

In synthesis, 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 observed lower reach entrenchment and the consequences that may be expected for this misfit channel configuration are discussed, as follows, in the general context.

5 Discussion

Both exposed cases represent examples of the response to human interference in the river system. Although the importance of other widespread basin changes cannot be excluded, the main issue for damage occurrence increase has been determined by construction works such as road and channels rehabilitation. Altogether in both cases the situation can be expressed in terms of the relation 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 local factors, causing sudden sediment deficit or sediment excess (Hooke and Mant, 2000).

In the Rivillas flood, deposition is associated particularly with erosional sources, very punctual, and with tributaries which deliver new sediments to the main channel by means of lateral fans (Fig. 8a). The relationship between anthropogenic changes in the floodplain and increased stream power is clear in the Rivillas and La Azohía streams. Track roads have a direct and immediate effect downstream as it has already pointed out by Hooke and Mant (2000) who refer major scour on the downstream side of most tracks and crossings. This local scour could be much greater than mean scour (Foley, 1978). In the Rivillas flood, we found a gradual increase of stream power in lateral road constrictions, being different as the one in crossings or small bridges, with an inmediate effect downstream. In the same way, any other human modifications such as artificial straightening or channelization do not immediately cause increased erosion, even if the stream power increases, but erosive features appear some tens of metres downstream.

The transformation of stream morphological parameters (width, depth and gradient) as well as of the channel pattern conditions energy balance during flood events. However, as indicate by Hooke and Mant (2000), extreme events are not required to generate significant changes while the most destructive effects are achieved with avenues of medium to high size. These changes in channel and planform morphology may be considered in studies prior to the occurrence of a flood event (modelled response case) in order to predict analogies to those found after a real event (observed response case).

In La Azohía fan approach, the second studied case (modelled response), results show that there is a tendency to concentrate the flow in a narrow and deep channel. This situation could be due to the overall trend presented in Spanish rivers by Garzón and Alonso (2002), Liebault and Piegay (2002), Uribelarrea et al. (2003) and Hooke (2006), with general entrenchment and confinement in the channel domain, and less deposition in floodplain areas. But this circumstance is better associable to permanent channels then to ephemeral streams on distributary alluvial systems, as the one here described. Besides, check dam construction and reforestation have been suggested as causes of the extended narrowing, but these do not exist in the Azohia watershed and could only explain general incision.

Besides, Azohía main channel entrenchment cannot be related either to a fan rejuvenation stage resulting of an intrinsic geomorphic threshold exceedence due to the fan over-steeped gradient. Therefore other extrinsic geomorphic thresholds should be analysed for this fact such as tectonics, climate, land use changes or anthropogenic interference. Considering the tectonic aspect Maher and Harvey (2008) suggest that tectonics combined with sea level changes and are responsible for morphological changes in the nearby ephemeral Alias River.

In addition, Azohía main channel entrenchment cannot be either related to a fan rejuvenation stage resulting from an intrinsic geomorphic threshold exceedence due to fan over-steeped gradient. Considering other possible extrinsic geomorphic thresholds, Mather and Harvey (2008) have suggested that tectonics combined with sea level changes are responsible for morphological changes in the nearby ephemeral Alias River. These changes, however, refer to lower reach transformations during the past thousand years, and not to changes in our time scale deduced from aerial images for the last 50 yr.

In a simplified picture, the present fan situation involves a channel pattern change from wide and shallow channels versus flows concentrated in a single channel. This transformation would be the one resulting of a decrease of load availability which implies a stream section controlled by discharge rather as by load. Several works have been undertaken in the fan area capable to convey water flow into one single channel. As showed in Fig. 6, former distributary channels on the fan have disappeared induced by human flood control activities. In La Azohía case, the loss of secondary channels is due to the artificial debris storage in the central fan area which obliges the waters under flood situations to flow towards the main course. Longitudinal defences, as well as roads and protections walls, help also water convergence into the main channel. This situation also occurs in the alluvial plain of the Rivillas River (Fig. 8c), where secondary flood channels have disappeared in most cases, either by reworking and filling for agricultural purposes (Ortega and Garzón, 2009a) or by direct urban construction in the riverbed.

Another cause of great influence is the observed channel bed reworking in the mouth of the main channel as a result of river alteration works to drain more water during flooding. These works have removed some of the sediment from the channel, forcing headward erosion in the main channel, which is being eroded and entrenched.

In addition, as a damage enhancer, we believe that the recent abandonment of much agricultural land in alluvial sections has prompted an increase of shrub-like vegetation. As observed by Hooke (2006) for SE Spain and other Mediterranean areas, this fact has reversed main stream processes, reducing sediment load contribution to channels and favouring soil erosion and washing out of sediments, especially in the final reach.

6 Conclusions

In ephemeral streams, medium and high flash-floods reveal the effect of human impacts on different scales: river and watershed. After a flood, erosional processes appear more frequently in reaches that have undergone more changes as a result of human impacts. Percentages of erosive areas are up to twice those of less anthropogenic sections, mainly affecting floodplains and channels. Deposition is associated particularly with erosional spots in the basin and with tributaries which deliver large amounts of sediments to the floodplain.

Disruption of the channel pattern changes river connectivity and scouring occurs as a consequence of excess energy. This energy surplus is focused at weak points downstream of anthropic disturbances. Riparian vegetation is an energy sink, so that deforestation alters the balance and affects the available energy. Reaches with more riparian vegetation show less erosion than deforested reaches. In some cases, however, the excess of deposition due to riparian trapping reduces channel capacity and triggers overbank flow and channel diversion. Erosion appears in localized areas downstream of the stream power peak, and this peak is very much related to human modifications, especially dirt roads and small bridges which constitute flow obstacles. If there is a lateral road causing continuous longitudinal constriction, there will be an increase in stream power downstream, but the distribution of erosion peaks is spotty and occurrences are isolated; there is no continuous pattern. Channel realignments do not affect the stream on the spot but a few tens of metres downstream. Sedimentation on the floodplain follows an irregular pattern. We think this process is very much influenced by erosion in tributaries and the presence of lateral fans delivering more sediment. Flood hazard is increased by aggradation on the channel margins in the form of overbank deposits, which reduce evacuation capacity. Absence of erosional and depositional features is more probable in well preserved reaches, while there are fewer areas without morpho-sedimentary changes in human affected reaches.

As in the Azohía case, human-induced local changes in ephemeral channels can remain dormant in the river over long periods of time. Recent afforestation and abandonment of land reduces the sediment load, thus altering the energy distribution and focusing the changes in the main active channel. The convergence of all the activity in the main channel during small flood events alters its natural morphology. The transversal section changes from a high to a low width/depth ratio, producing a deeper, narrower channel that becomes more entrenched as energy is concentrated in the channel bottom.

Parameters such as stream power and shear stress can reveal changes in fluvial dynamics caused by human activities that remain latent in the absence of a flood large enough to trigger the occurrence of a new geomorphic adjustment.

Within an ephemeral channel there are many local changes in the energy balance, some of natural origin, such as expansions and narrowing and other of anthropic origin, such as pipelines, bridges and tracks. The relationship between erosion and sedimentation in the basin is highly variable, and even within a same reach, but in general terms it can be concluded that the natural channels are much more adapted for floods than human modified sections. In the last, the balance almost always tends to result in increased production of energy, and thus scour generation. Analysis of the anthropic influences in ephemeral streams in Spain shows that natural channels are much more adapted for major floods that those sections who are not human modified.

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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 parenthesys 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 %)

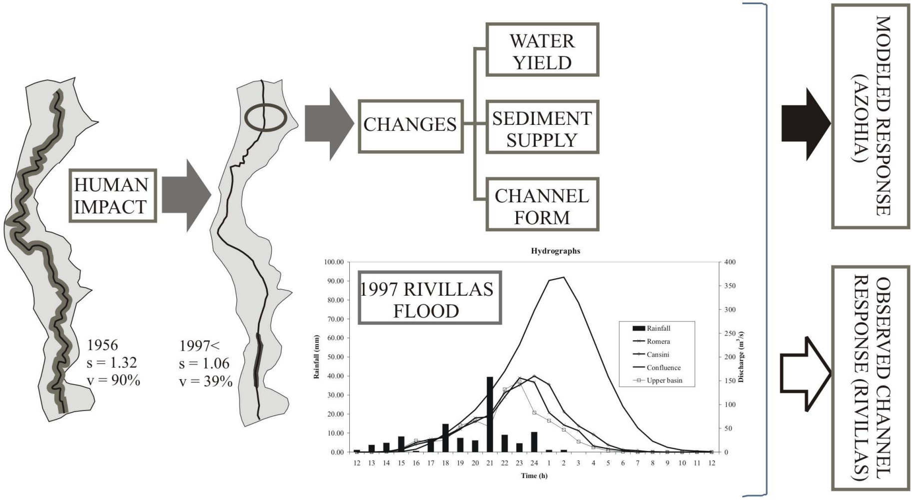

Fig. 1. Conceptual model of the study. Antrophic impacts determine changes in water yield, sediment supply and channel form that can be modelled hydraulically for an observed and hypothetic response.

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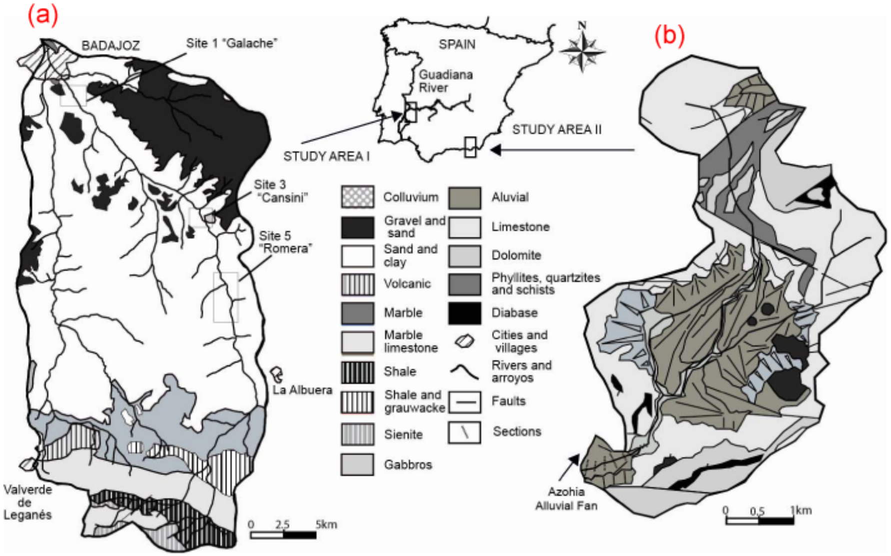

Fig. 2. Map location of the two studied areas, **(a)** Left, Rivillas watershed and geological map, **(b)** Right, Azohía watershed and geological map.

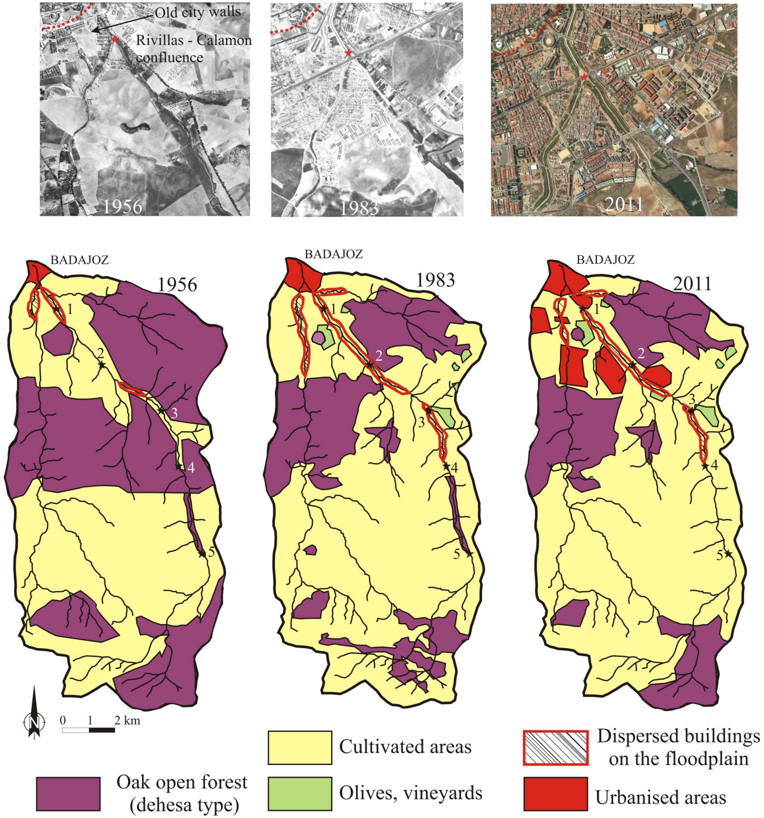

Fig. 3. Land use changes in the Rivillas basin between 1956 and present day based on aerial photographs and urban evolution in the Rivillas and Calamon Rivers near Badajoz city. Location of studied reaches: 1 Galache, 2 Acuapark, 3 Cansini, 4 Romera, 5 Huerta Peña.

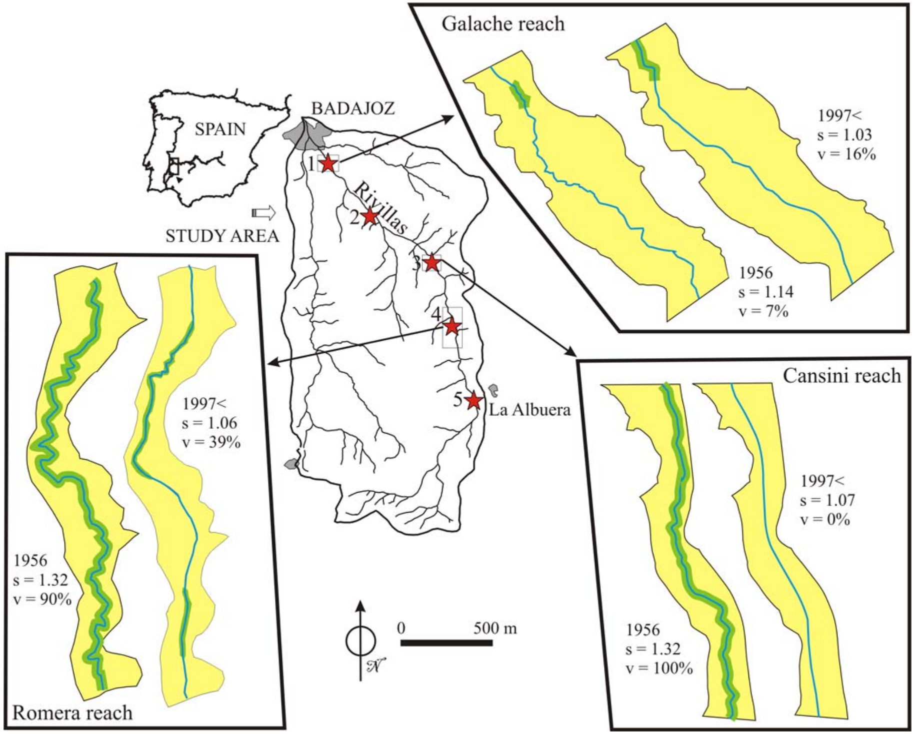

Fig. 4. Situation of the studied reaches in Rivillas River: Galache (1), Acuapark (2), Cansini (3), Romera (4) and Huerta Peña (5). Changes between 1956 and 1997 in channel sinuosity and riparian vegetation in three selected sites on the Rivillas watershed is shown.

Fig. 5. Aerial photographs comparison in the Azohí a alluvial fan between 1956, 1997 and 2004.

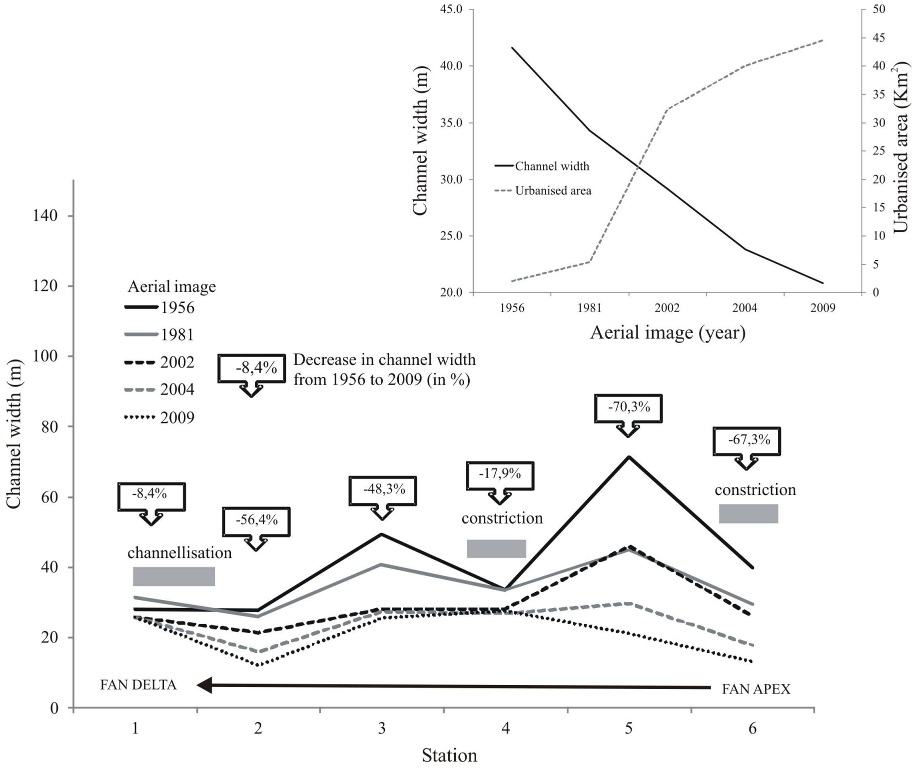

Fig. 6. Changes in Azohía fan due to urbanisation. The upper graphic shows channel width decrease in relation to the increase in urban occupation.The lower long profile graph reflects that width changes are more related to open sections without a bedrock control and less changes are related to chanellisation.

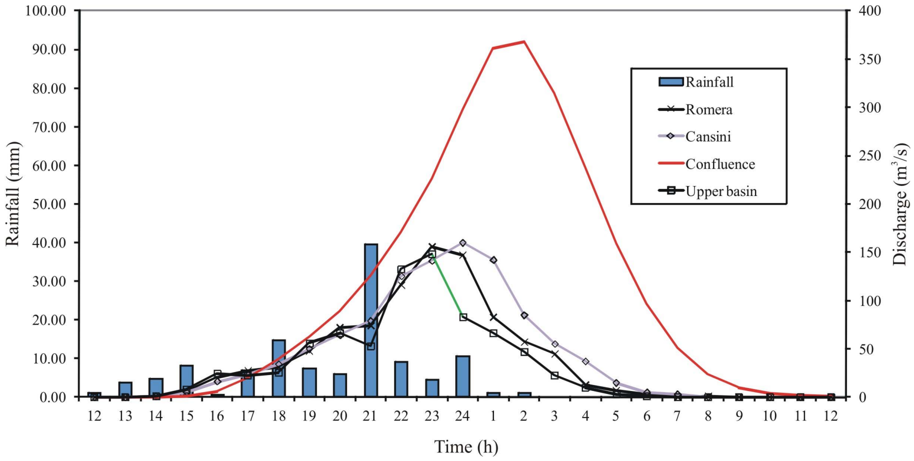

Fig. 7. Rainfall distribution and hydrograph of the 1997 flood event for the upper, medium (Romera and Cansini reach) and lower reaches (confluence) at the Rivillas basin.

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)** antropic flow limitations in floodplain secondary channels (Acuapark reach), **(d)** natural overbank sedimentation favoured by riparian vegetation (Romera reach), **(e)** antrohopic 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).

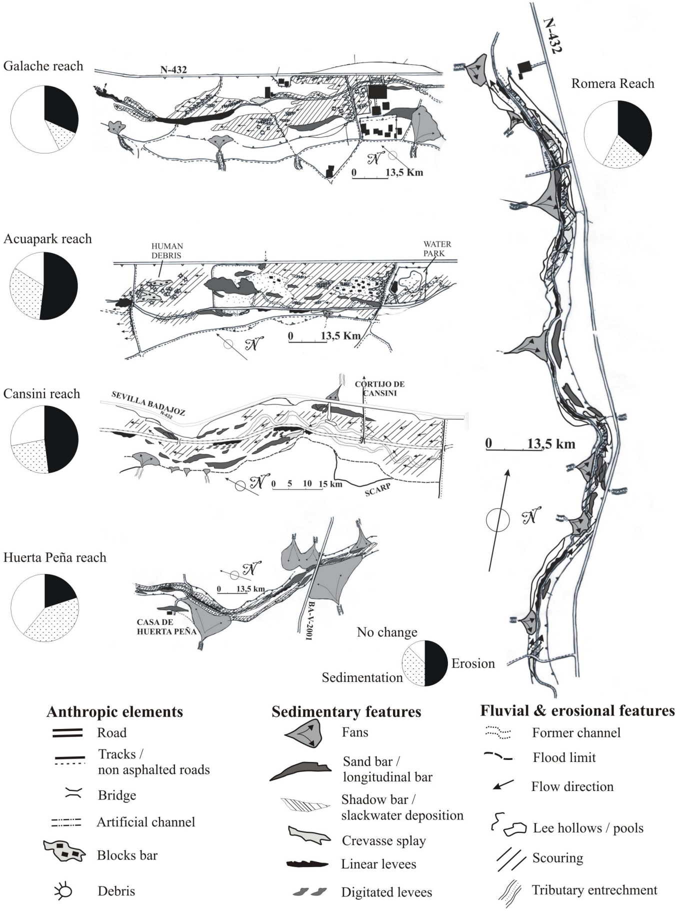

Fig. 9. Distribution of erosion and sedimentation features along selected reaches and antropogenic disturbances on the floodplain in the Rivillas River. See Fig. 2 for location.

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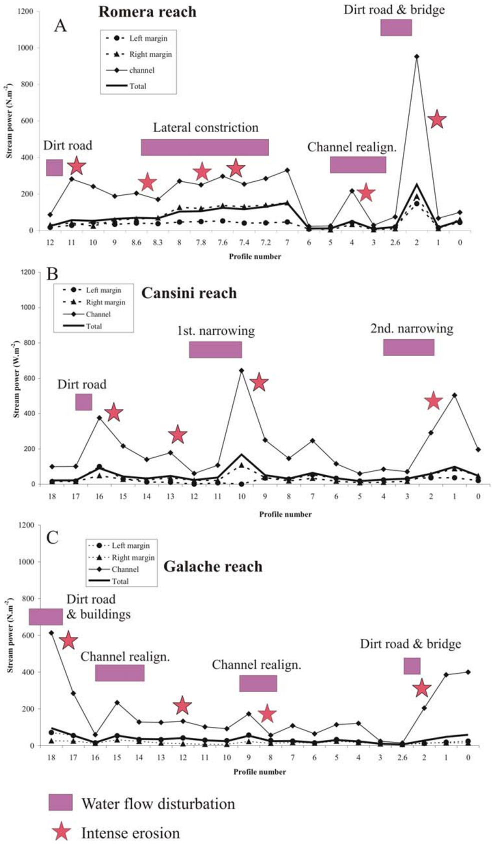

Fig. 10. Influences in stream power values of three selected reaches from upstream to downstream in Rivillas River: Romera **(A)**, Cansini **(B)** and Galache **(C)**. Human disturbances and intense erosion sites are located in the longitudinal profiles.

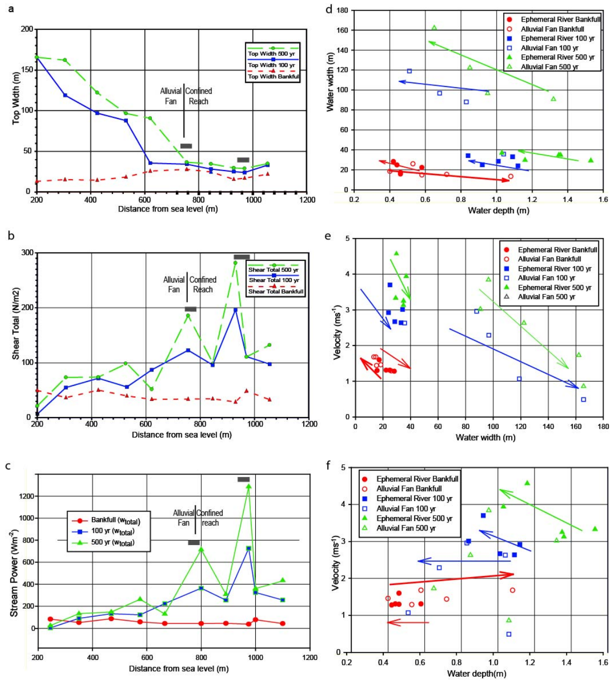

Fig. 11. Results of selected variables in the Azohí a Rambla in the three considered scenarios, **(a)** flow width changes in longitudinal profile, **(b)** water width-depth ratio, **(c)** water depth in relation to flow velocity in channel, **(d)** water width in relation to flow velocity in channel,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