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Review

Geomorphological and sedimentological analysis of flash-flood deposits The case of the 1997 Rivillas flood (Spain)

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ABSTRACT

On the basis of the description of the 1997 Rivillas flood deposits, a morphosedimentary feature classification is proposed. Mapping of the main morphosedimentary deposits in seven reaches along the basin has provided abundant data for each defined typology and for a better adjustment of their stability fields. Because of their unstable preservation environment, immediate post-flood field surveys with descriptions of erosive and depositional features were undertaken. Up to 18 features were classified as either sedimentary or erosive and mapped according to their genetic environments. Anthropic interference such as land use changes produce modification of sediment supply and in channel and floodplain erosive processes causing flash-floods to be more catastrophic. Erosive features are dominant over sedimentary ones, as the sedimentary budget in the river is negative. By means of HEC-RAS (Hydrologic Engineering Center) modelling, we were able to obtain mean values of the main variables limiting feature stability (velocity, depth, stream powers and shear stress). These provide information regarding maximum stability threshold and peak flood discharge. The ephemeral nature of riverine flash-flood deposits in this type of setting does not mean that they are not significant, and their interpretation after recent floods can significantly improve interpretation of the event dynamics and its flood hydrology and also be useful for flood risk mapping.

1. Introduction

A flash-flood represents an abrupt and short duration rise in the discharge of a stream with a dramatic contrast among the event and the extended period between floods (Reid, 2004). The geomorphic effects of flash-floods are significant especially if the event offers a long lasting peak discharge (Costa and O'Connor, 1995). The term flash-flood embraces several types of processes and geomorphic environments, such as ephemeral streams (Greenbaum et al., 1998) or alluvial rivers and fans, but the literature is more concerned with bedload dynamics (Reid et al., 1998) or quantification of sediment–transport ratios (Cohen and Laronne, 2005). Flash-floods have also been studied from various perspectives, such as their meteorological control (Harnack et al., 2001), or as paleohydraulic approach for peak discharge (Baker, 1973, 1978; Costa, 1983).

Flash-floods are usually related to ephemeral streams, and the Bijou Creek paper on flood deposits (McKee et al., 1967) was taken as an example for flashy, sheetflood sequence in a slightly modified model by Miall (1977, 1996). Recent flash-floods deposits typically have been described related to alluvial fans and pediments in semiarid environments (Lucchitta and Suneson, 1981, Sneh, 1983; Stear, 1985) consisting of a complex flow pattern of channel and sheet-like deposits related to open, distributary (spreading out) systems, although a special case of confined flash-flood deposits has been also described by Sneh (1983).

As Stear (1985) pointed out, an important aspect that needs to be stressed is the erosional effects of these catastrophic floods. In the present study, we are dealing with a narrow alluvial plain confined by valley slopes where erosional processes dominate over the depositional ones. Although the flood deposits in these ephemeral streams environments have low preservation potential, their interpretation can notably improve the understanding of the flood dynamics and hydrology.

In November 7th 1997, one of the most destructive floods occurred in the Iberian Peninsula during the 20th century in the Rivillas stream, affecting the town of Badajoz (Fig. 1). The flood caused 23 deaths and material losses estimated at $150 M USD. These figures were unexpected for a 34 km long tributary of the Guadiana River, with a low relief drainage basin of 314 km^2. The disastrous character of the event was assumed to be related to the flashy character of the event and the land use on the floodplain. In fact, a shift toward intensive farming at the watershed have been made, and the active channel running through a built up area had been channelized, thus favouring human occupation of the banks (Ortega et al., 1998).

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Because of the low preservation potential of the flash-flood deposits, field surveys were conducted immediately after the event. Detailed descriptions of the erosional and depositional features were carried out for comparison with the hydraulic flood analysis. A morphosedimentary classification of scours and deposits is proposed here on the basis of the descriptions of the 1997 Rivillas flood deposits.

The first objective of this paper is to establish a classification of geomorphological and depositional features considering their spatial distribution that might be useful to analysis of other flash-flood events in similar environments. It is not our intention to present an exhaustive literature review, but to provide a systematic description and analysis of the 1977 Rivillas flood that could be use as a reference for further studies on the flash-floods.

Another aim is to identify features generated during the maximum flood discharge in order to achieve more information of overbank sediment deposits, like Walling et al. (1997) suggest. Several authors have dealt with the subject of trying to relate sedimentary features to flow parameters, among them Leeder (1982) and Miall (1996). Shouthard (1975) and Costello and Southard (1981) tried to establish relations between water depth and bedforms. Dalrymple et al. (1978) and Shouthard (1975) related features to flow velocity, and Ashley (1990) related them 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. Baker and Costa (1987) established relationships between stream power and incision or degradation, and recent studies have addressed geomorphic changes and effectiveness (Costa and O'Connor, 1995).

The analysis of the hydrologic and hydraulic data of the Rivillas flood was a prerequisite to interpret the factors controlling the spatial distribution and characteristics of the observed erosional and depositional features. In our study, HEC-RAS (Hydrologic Engineering Center) hydraulic modelling was used in combination with high-water marks measured after the flood, applying analogous techniques as the ones used for palaeohydrological estimation (Patton et al., 1979). Finally, we tried to elucidate what information can be inferred from each feature for interpreting flood characteristics peak flood parameters. We used the results obtained with HEC-RAS modelling to estimate the most significant variables, such as depth, velocity, shear stress and stream power in morphosedimentary features stability fields under which bedforms are preserved. Hydraulic modelling has been shown to be useful to determine floodplain flow characteristics (Siggers et al., 1999), distribution of flow velocities across the floodplain (Gee et al., 1990) or to predict net floodplain deposition (Moody and Troutman, 2000).

Finally, there is an interesting issue from the applied perspective to determine flood behaviour at particular sites including constrictions. During high magnitude floods, in confined valley reaches, like the studied one, there is a great variation in hydraulic conditions and flood hazard severity along the floodplain; especially due to its complex microtopography and morphology (Walling and He, 1998).

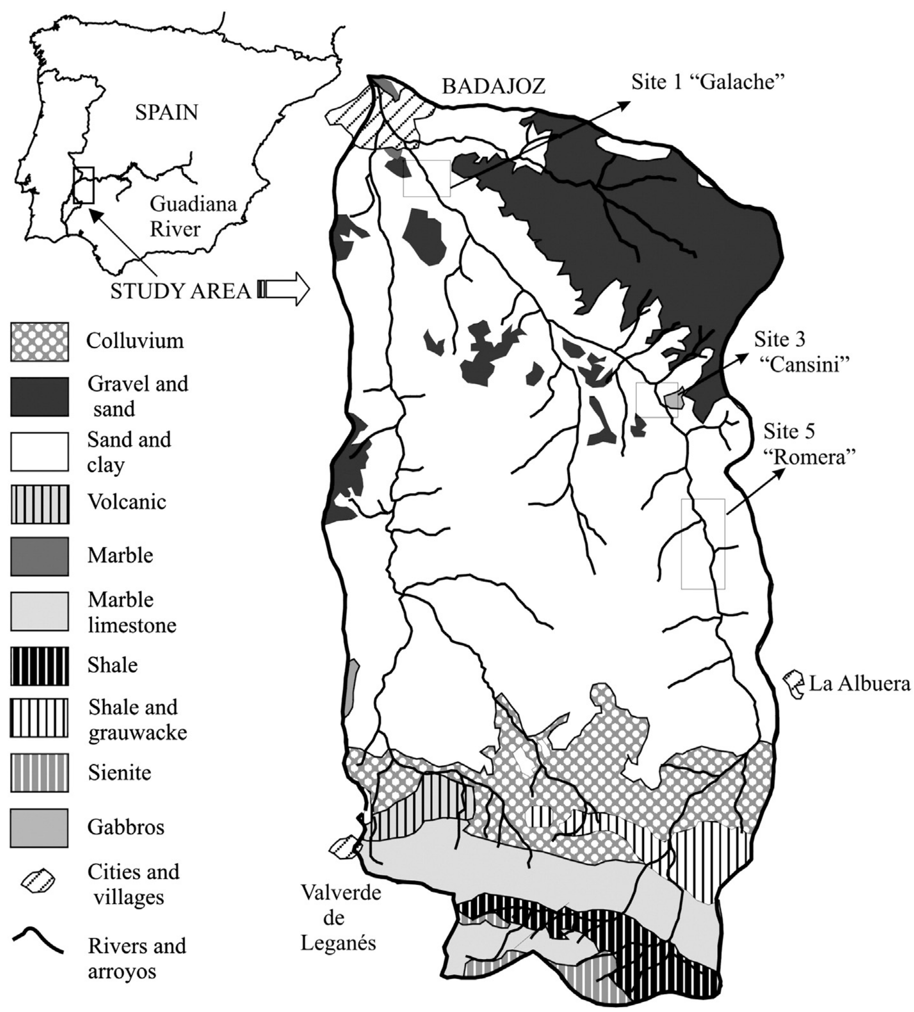

Fig. 1. Location of the study area and geological sketch of the Rivillas Stream.

2. Regional setting and the 1997 flood event

The Guadiana River, with a drainage basin of 66,800 km^2 and semiarid conditions (rainfall 400–500 mm/y), is one of the largest in the Iberian Pensinsula; it is the fifth in terms of discharge and length. It crosses the Península from east to west through various geological units before flowing into the Atlantic Ocean. The Rivillas stream is a 34 km long tributary of the Guadiana River with a basin of 314 km^2 and an average gradient of 0.0075 m/m. The Rivillas main tributary is the Calamon Stream. It has a similar size and length, so that the peak discharge tends to occur at the same time at their confluence located in Badajoz urban area, converging a high hazard and exposure.

From a geological point of view, most of the basin is excavated in fine-grained Tertiary detritical sediments. Only the headwaters present outcrops of metamorphosed limestones and shales (Fig. 1). An important fact, that affects the sedimentary forms, is the constrictions and modification of the river course, so that the flood waters flow is different from the normal pattern of overbank flow and sluggishness over the floodplain. In this case, the alluvial plain actually works under flood conditions as a high velocity channel of flow in semi confined environment.

On 5–6 November 1997, 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. The precipitation event reached a high intensity since a significant part of the rain fell in 1 h (Fig. 2). Moreover, all nearby rivers in Spain and Portugal produced floods with catastrophic results in terms of human and material damage: 23 deaths in Spain and 10 in Portugal.

The antecedent rainfall was also heavy, exceeding 84 mm in the previous 3 days. This fact combined with the intense rainfall and the confluence of the large Calamon tributary stream at the lower part of the Rivillas basin within the built up area produced a very rapid rise in the floodwaters. There was a lag of barely 2 h between rainfall and flood peak in Badajoz.

The end result, in geomorphological terms, was a drastic transformation in the floodplain, with the creation of numerous depositional and erosive forms described and analyzed in this paper.

3. Methods

Fieldwork after a flash-flood needs to be as quick as possible in order to describe the generated features before they are disturbed. This is not only because of human activity, including recovering and ploughing the floodplain, but also, because the large growth of vegetation in the fertile floodplain soils that causes rapid alteration of the flood features by bioturbation.

A reconnaissance survey of the river reaches where geomorphic impacts were greatest was undertaken immediately after the flood occurred. Seven reaches were chosen as representative of the upper, middle, and lower basin sectors. Some other reaches were selected because they presented high anthrophic occupation and transformation, where peculiar features controlled by the influence of human elements were formed. The length of the selected reaches ranged from 2 km to 500 m. Features in these areas were described and mapped, and in some cases, a detailed topographic survey was undertaken in order to perform HEC-RAS hydraulic modelling.

Morphosedimentary features were mapped in each reach on a 1:4500 scale topographic map, showing only features large enough to be mappable at that scale. The river layout as it was in 1956 (the date of the oldest available aerial photographs) and the present river, mapped after the flood, was also established. In addition to the map of morphosedimentary features, maps of every reach were carried out by interpreting aerial photographs taken in 1956 and 1982 (most recent available aerial photographs). Basin changes were identified comparing both maps. This comparison allowed us to determine, whether the morphosedimentary features were present or not and to infer an aggradation–degradation balance for the river.

Two methods were used to estimate the peak flows of the 1997 flood. The first was a unitary hydrograph using the HEC-1 programme, which produced an estimate of 653 m^3s^{-1} for peak discharge; the hydrograph is shown in Fig. 2. The second one was an hydraulic method using HEC-RAS programme yielded a peak discharge of 799 m^3s^{-1}. We believe that the latter is more accurate given that it was verified with flotsam data in three zones outside the built up area. The peak discharge derived from the unitary hydrograph was dependent on theoretical estimations of the number of curves method and precipitation data that were not uniform all over the basin.

Finally, we used HEC-RAS hydraulic modelling in order to estimate some hydraulic parameters of the flood and relate them with the depositional features. Flood peak discharge was estimated in three of the analysed reaches. These were selected based on the variety of features and because they are distributed representatively along the 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

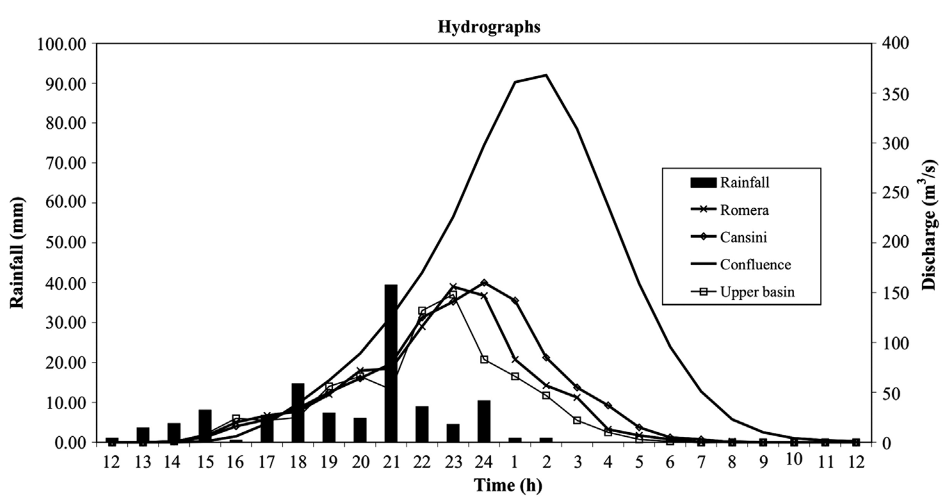

Fig. 2. Rainfall distribution and hydrograph of the 1997 flood event for different sites at the Rivillas basin.

subcritical flow type was considered. Energy losses were calculated from roughness using the table for cultivated areas presented in Chow (1959), 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, 1978). Those field measurements considered less reliable owing to the proximity of perturbations (such as buildings, fences, etc.) were discarded.

4. Watershed and floodplain anthropogenic changes

From the comparison between the 1956 and 1982 aerial photographs and from the basin situation after the flood, several changes were identified. The most important land use changes and damage occurred at Badajoz city, which achieved urban expansion mainly by spreading out over the Rivillas and Calamon floodplains. The scale of the disaster was also favoured by the false sense of safety induced by the channelization of the streams. A remarkable aspect to take into account, however, is the extraordinary scale of the damage to the city, not only because of the presence of buildings but also to the increase in bedload induced by anthropic changes upstream.

The land use changes in the basin consists mainly of removal of the original vegetation cover, changes of crop types, floodplain transformation, and road construction. Comparison of aerial photographs has revealed that changes were particularly dramatic in the previous years, and their direct effect on the floodplain can be observed on stream reaches showing direct anthropic influence.

Anthropic and land use changes may be differentiated as affecting the basin or the floodplain. The principal alterations in the basin are a consequence of the conversion of "dehesa-type" open forest pastureland into vineyards and olive orchards, especially on hillslopes. This fact favoured intensive soil erosion and removal of large amounts of sediment into the floodplain leading to the development of small of alluvial fans on the flanks of the floodplain in the first stages of the flood event.

On the alluvial plain, the principal changes consisted of channel realignment with meanders obliteration and removing of riparian vegetation. Some of the results of these changes can be seen on the Cansini and Romera reaches (Figs. 3 and 4). Sediment delivery increased from valley side slope enhanced alluvial fan deposition on the flanks of the floodplain. The river's sinuosity was reduced from 1.32 to 1.07, producing local floodplain erosion with the 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 riparian vegetation had grown on the stream banks without restraint from the abandonment of pastures, channel constriction and reduction in flow capacity occurred. In addition, anthropic constructions (such as causeways, bridges, roads, and buildings) also limited the flow capacity of the channel and floodplain.

5. Morphosedimentary features

The morphosedimentary features recorded on the field were used to produce maps (Fig. 5) and to interpret and classify the identified features. A total of 17 features either depositional or erosive were classified (Table 1) and subdivided according to their spatial location. Feature size was also considered on the following scale: macroform (decametric), mesoform (metric), and microform (decimetric).

Depositional features were mapped and classified into three geomorphic environments: channel bank, floodplain, and slope deposits. Twelve groups of deposits are described according to their architecture and location in relation to the river and their genetic interpretation on the basis of texture, structure, size and depth, and lithofacies (Miall, 1996). Five types of erosive features were found and have been classified as scours, pools, and channel incisions. The origin of most of them, however, is controlled by anthropic activities or structures on the alluvial plain.

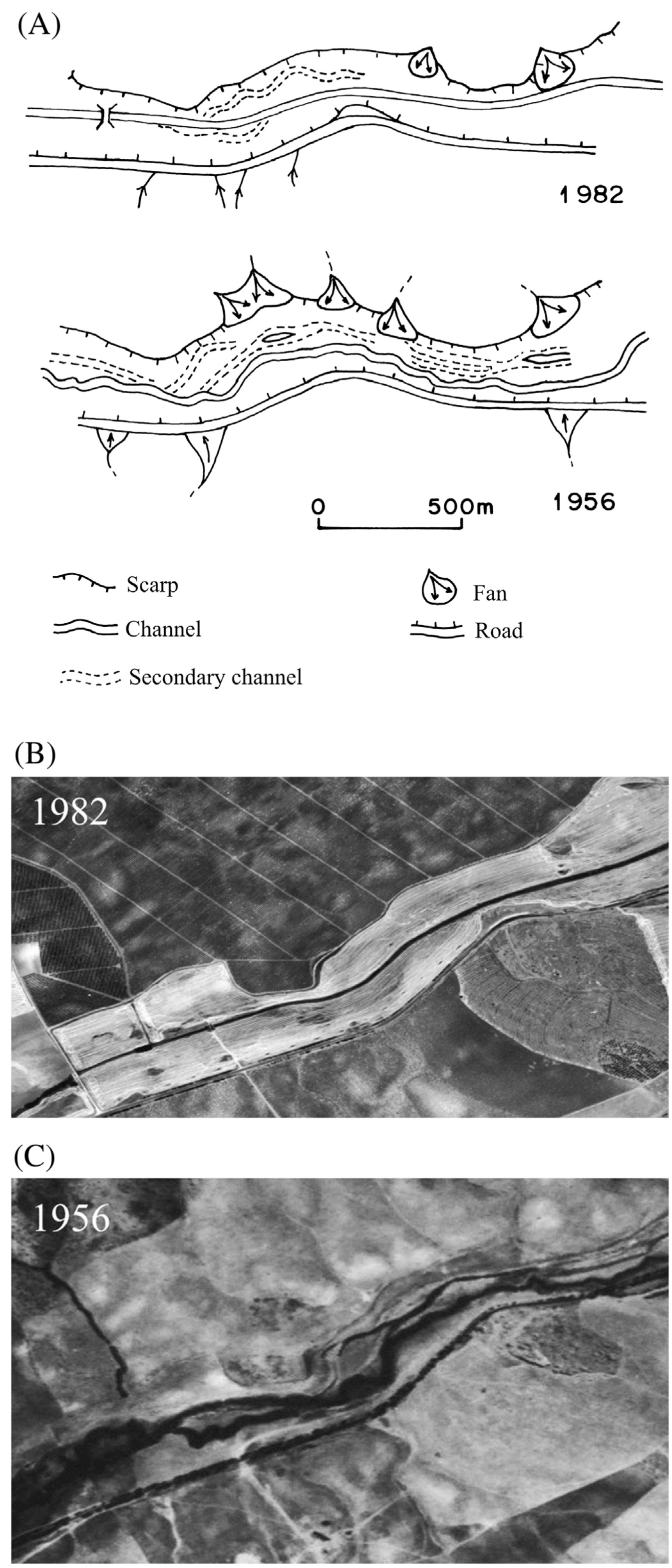

Fig. 3. Changes occurred at the Cansini reach between 1956 (A) and (C) when the channel was sinuous and 1982 (A) and (B) after channel straightening and intensive farming.

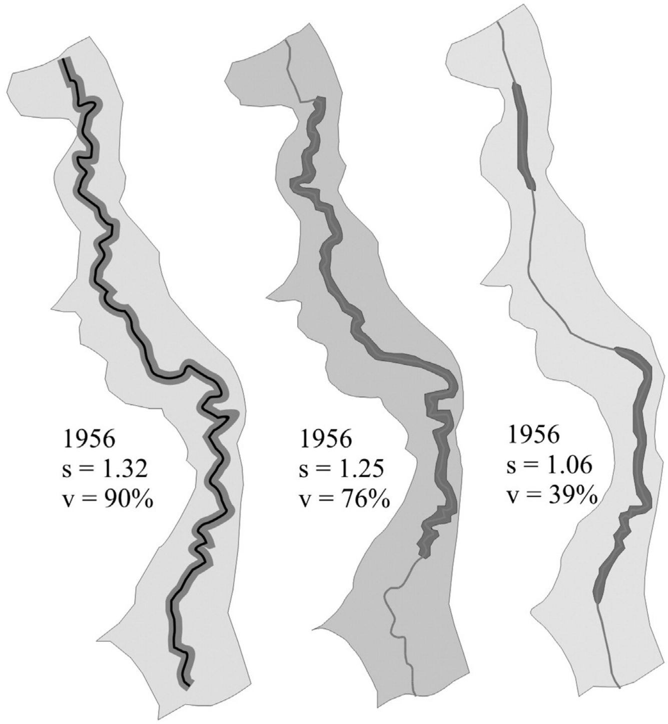

Fig. 4. Anthropogenic changes in stream sinuosity index (s) and riparian vegetation cover (v) in Romera reach between 1956 and 1997.

The first geomorphic environment considered, channel bank deposits, are related to ordinary channel water outflow onto the floodplain. They commonly build up in the early stages of the flood and are subsequently reshaped. Under natural floodplain conditions, the largest grain sizes are generally deposited on the channel banks, and finer sediments spreads over the floodplain. In the case of the 1977 Rivillas flood complex morphologic adjustments occurred, due to confinement of the channel by relatively high, artificial sandy levees and anomalous riparian vegetation and to the narrowness of the floodplain, which confined the flood instead of causing energy dissipation. To our knowledge, some of the features developed by the Rivillas flood have not been described in the literature before. Three types of channel bank depositional features have been identified: crevasse splays, linear levees and "digitated" levees.

5.1. Crevasse splays

In this group we included the crevasses splays that had not been reworked. They present the characteristic crevasse splay morphology (Miall, 1977) and coarse sand and even granules and pebbles showing a progressive decrease in the grain size away from the outlet (Moya et al., 1998a).

Numerous examples of this type are found on the banks, as the channel's efficiency was only 2% of peak discharge. Consequently, from the earliest stages of the flood, there was overbank flow and generation of crevasse splays of sizes ranging up to 160 m long and 30 m wide, although some later evolved into longitudinal bars (Fig. 6). They have been found in most cases associated with anthropic changes in channel curves and direction, but they also occur under natural conditions such as channel constrictions and expansions.

5.2. Linear levees

Linear levees are natural levees formed by immediate overbank accretion of coarse sands granules and pebbles as classically described in the literature (Singh, 1972). However, they present extensive continuity along the artificially straightened channel, favoured by anthropogenic

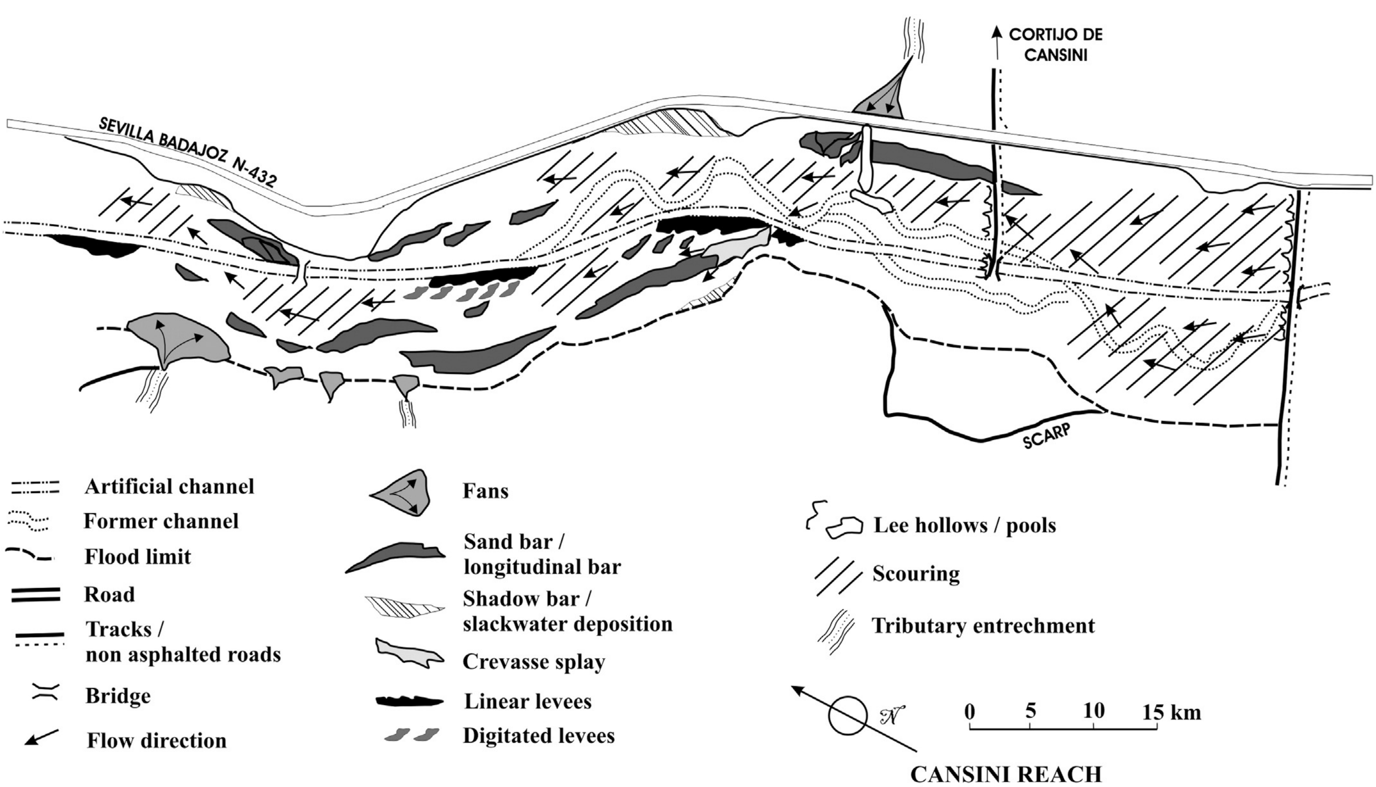

Fig. 5. Map of sedimentary features in the Cansini reach. Arrows show main flow direction during the flood describing a meandering trajectory.

Table 1
Morphosedimentary features classification.

Process	Location	Architecture	Grain size	Feature	Size
Sedimentation	Floodplain	Sand flats	Sand	Sand flats	Macro and mesoform
		Bars		Longitudinal bar	Macroform
				Semilunate bar	
				Shadow bar	Mesoform
			Gravel	Longitudinal	Macro-
				Transverse	mesoform
			Mudball	Longitudinal	Mesoform
	Channel bank	Splays	Sand	Crevasse splay	Macroform
				Linear levees	Mesoform
				Digitated levees	
	Lateral	Alluvial fans	Sand and gravel	Symmetric fans	Macroform
				Asymmetric fans	
Erosion	Floodplain	Scours	–	Longitudinal scour fields	Macroform
				Lee hollows	Meso and microform
	Channel and floodplain	Pools		Pools (kolks)	Mesoform
	Tributaries	Channels		Tributary entrenchment	Macroform
	Channel			Former channel entrenchment	Macro and mesoform

accumulation of channel dredging deposits and agricultural dumps. They reach 50 m in continuous length and 40 cm in height.

5.3. Digitated levees

Changes in riparian vegetation, cultivation practices and the presence of abundant loose sediments have favoured the development of a peculiar type of levee designated as "digitated levees" (Moya et al., 1998a,b). These special sigmoid levees, derived from the linear levees, present a discontinuous elongated and finger like morphology as they are reshaped during advanced stages of flooding.

A former linear levee is split into discontinuous forms that evolve as shown in Fig. 7. The initial continuous levee is spread out into a special type of crevasse splay and reworked by floodplain longitudinal flow that elongates the deposit downstream. When flooding subsides, the reversed flow that returns into the stream channel from the floodplain dissects the features, reshaping their morphology into a digitated form. These deposits consist of coarsening upwards and planar cross-bedded medium size sands, with intercalated beds of fines. They reach up to 13 m in length and 50 cm in height.

6. Alluvial plain deposits

This group does not consist of ordinary overbank deposits related to outflows from the channel and leading to vertical aggradation like the regular bedsets described by Bridge (1984) as produced by discrete overbank floods. In the Rivillas stream, the narrow alluvial plain nearly functions as a channel during floods and the valley slopes are sometimes acting as channel banks. Under these conditions high energy forms develop on the floodplain. Within these alluvial plain we have recognised seven types of deposits: longitudinal, semilunate bars and sand flats (macroforms) and mudball bars, shadow bars, longitudinal and transverse gravel bars (mesoforms).

6.1. Longitudinal bars

Longitudinal bars are the most frequent depositional feature in all the river reaches and consisted of sandy accumulations elongated in the direction of flow but slightly curved. Most are built up by former crevasse splays deposits removed at the high-water stage. In the Cansini reach, several longitudinal bars have been formed as a continuation of crevasse splays (Fig. 6). The preservation of this type of depositional feature is favoured by the flashy character of the flood, which allows features to be preserved from hydraulic conditions, as proposed by Jones (1977) and suggested by Miall (1977) for the Bijou Creek model (McKee et al., 1967).

These bars are composed of medium to fine sands, occasionally presenting some coarser interbedded material from lateral supply. They have an elongated and narrow geometry reaching 180 m in length and 50 cm in height. Trough cross-bedding occurs and dune and ripple bedforms appear on the surface. The proposed origin involves the migration of material eroded from the levees that evolve into crevasse splay lobes that continue growing further downstream (Fig. 6). The stream-lined sand accumulation results in longitudinal bars with an undulating surface as they are not located in maximum flow velocity areas where erosion prevails.

Based on the location of the bars in relation to the channel and floodplain, we propose a sinuous flow model when the floodplain is entirely inundated. Flow sinuosity is possibly comparable to the model described by Simons et al. (1961) for flumes with large width/depth ratios, as we are looking at a similar situation of floodplain confinement on the Rivillas stream during peak discharge.

6.2. Semilunate bars

Semilunate bars are lateral or marginal bars developed at the floodplain margins. They are composed of fine sands and silts with parallel or low-angle bedding and rectilinear or sinuous ripple structures on the surface. They form narrow and elongated deposits up to 160 m in long and 30 cm thick, parallel to the river. We have not found individualised descriptions of similar bars in the literature, as these cannot be considered as lateral channel bars with tractive structures and relative high flow energy. Genetically, they could be related to slackwater deposits that result from flow dissipation in protected areas where deposits accumulate and preserve. Because flotsams are usually associated with them, they are good maximum water stage indicators, being their top surface 20 cm below the maximum flotsam height.

6.3. Sand flats

Sand flats deposits imply that the entire alluvial plain is acting as a flat, shallow, and homogeneous extraordinary channel while the ordinary channel provides a continuous overbank flow from its breached, confining levees. Sand flats were not very frequent; sandy accumulation features are located marginally to the channel and laterally to the floodplain. They are formed by composite bars and combined composite bars as described by Allen (1980). Cant and Walker (1978) suggested that they were produced by nucleation of small sandy bars, and Miall (1978) considered that they contained internal three-dimensional structures. Their main characteristics are fine to medium sands and silts with cross-bedding. Deposits are up to 10 m in length and 30 cm in thickness. Curved megaripples 1.5 m long appear on the surface (Fig. 8F).

In view of their marginal position, they are likely to reflect shallow water. In the sand flats located closer to the channel, where the water depth is higher during the peak flood, megaripples and composite and combined forms were developed.

6.4. Longitudinal mudball bars

A special feature caused by the intense erosion undergone by the floodplain is the formation of longitudinal mudball bars. These are produced by the erosion of the upper argillic horizon in patches to a depth of 30 cm. Although they are formed under natural conditions,

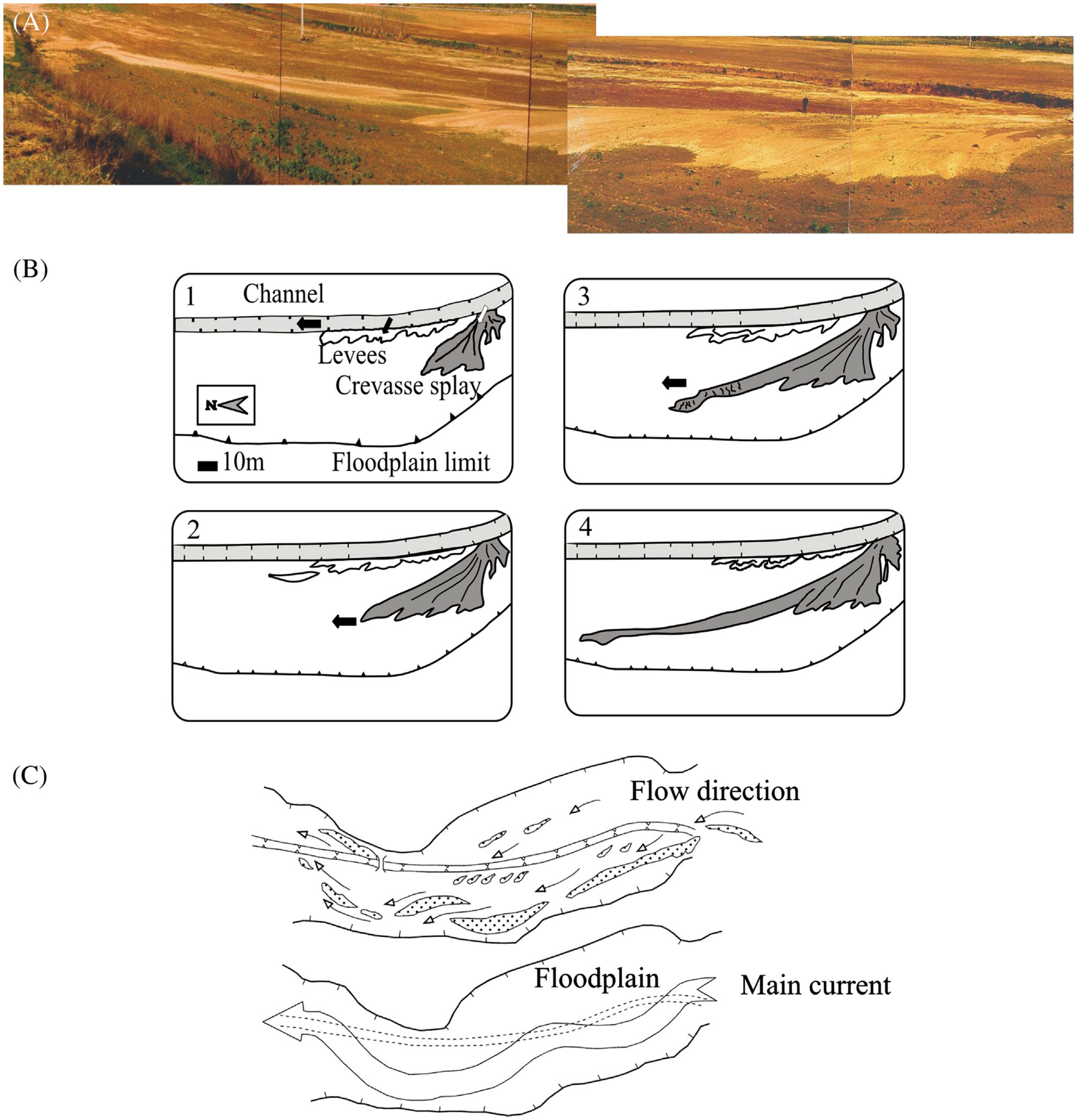

Fig. 6. Longitudinal bar development from a crevasse splay at the Cansini site. (A) General view of crevasse splay and longitudinal bar; (B) bar development stages; and (C) sinuous flow model and longitudinal bars distribution on the floodplain.

their origin has been favoured by changes in land use; like the elimination of former open forest (dehesas) and increased plugging depths achieved by modern equipment. The cohesive upper soil horizon is literally stripped away, and the eroded material deposited in the immediate proximity forms poorly developed bars. These bars are shallow and up to 40 m long. The mud clast may initially present imbrications, but they tend to acquire a subspherical shape in a short distance and become degraded loosing their shape further downstream (Fig. 8E).

6.5. Shadow or lee bars

The formation of these mesoforms is related to the presence of anthropic obstacles in the floodplain, such as wells, houses, and any structure that can cause flow diversion and the build up of a bar downstream. The deposits consist of coarse sand with no internal stratification or visible structures, and the length depends on the obstacle size with a maximum length of 6 m and a maximum thickness of 50 cm.

6.6. Longitudinal and transverse gravel bars

In spite of the lack of coarse material in the channel, some longitudinal and transverse gravel bars related to antrophogenic deposits have been found, including mill tailings from a factory and other types of dumping material.

Particle size is variable; but tabular, marble blocks up to 40 cm long have been observed showing imbrication fabrics. Bars may be up to

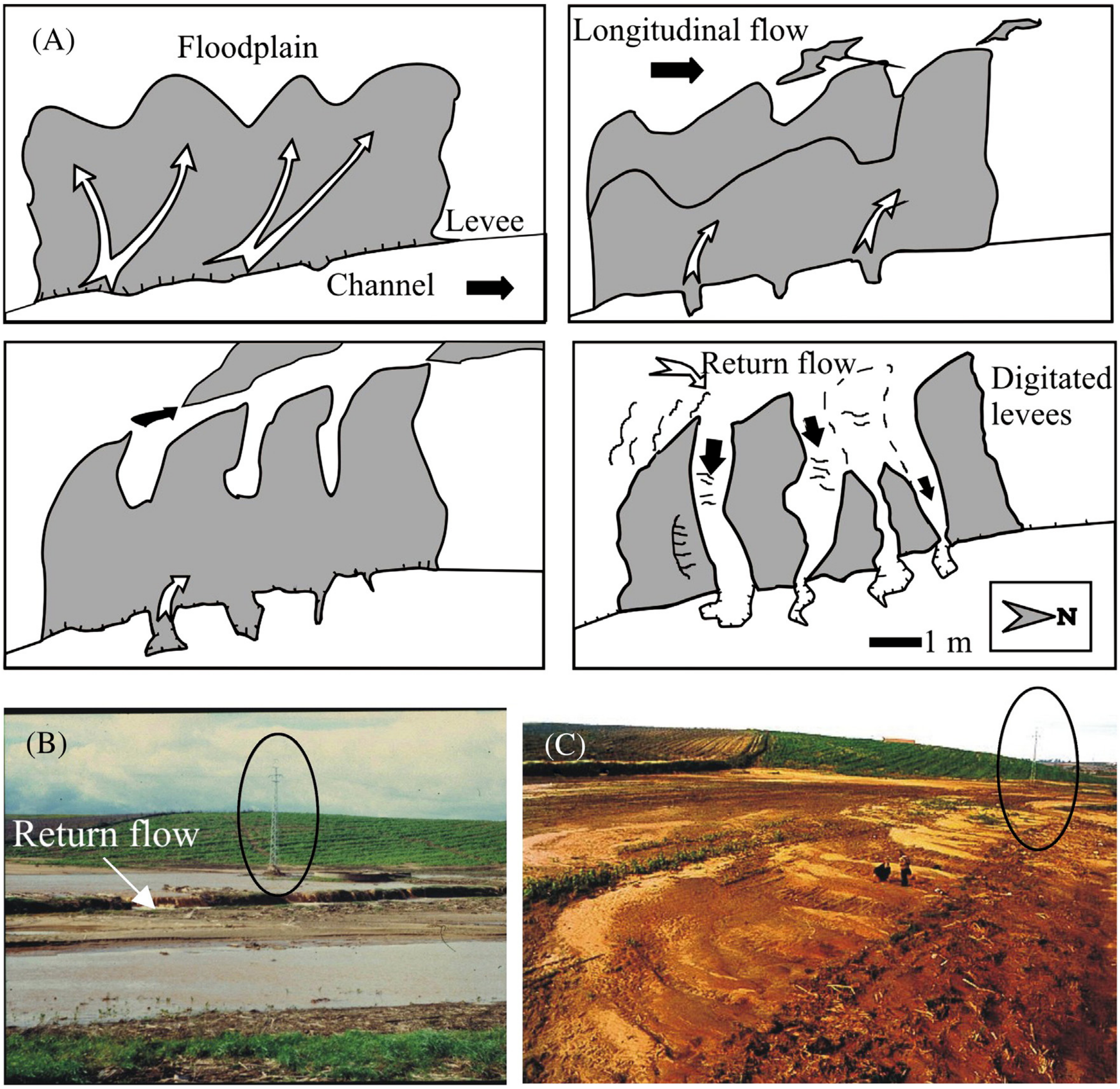

Fig. 7. Digitated levees. (A) Development sequence; (B) return flow from the inundated floodplain into the channel; (C) digitated levees view.

40 m long and 20 m wide. Their presence implies that the flow had enough energy to entrain and transport planar blocks. These particles were transported several hundred meters, revealing high energy conditions.

7. Hillslope features: alluvial fans

The entire basin is subject to intense slope erosion, favoured chiefly by deforestation and crop transformation. The sediment supply on the Rivillas floodplain increased considerably leading to the development of alluvial fans on the valley margins, which were later reworked by the flood acting as sediment sources. The alluvial fans studied here have been classified based on their plan view morphology into symmetric or asymmetric. Fans are present at the mouth of low order streams flowing, and those reworked by the longitudinal flow of the flood have attained asymmetric geometry. Deposits consist of alternating fine and coarse layers, 40 cm deep. Sinuous sand ripples are found on the surface.

Alluvial fans in semiarid zones receive large amounts of sediments during high energy flash-floods (Bull, 1977). In the Rivillas basin, sediment is largely derived from piping in the slopes (Fig. 8A, B), and stripping of argillic horizon stripping on cultivated crop fields or infilled creeks. Sediment supplies are greatest in areas of changed land use, such as vineyards and olive orchards with gradients exceeding 3%, together with “dehesa” open forest.

8. Erosional features

Five groups of erosional features have been identified; most of them are related to anthropic activities on the floodplain. These features may be located on the floodplain (longitudinal scour fields and lee hollows), on the floodplain and channel (pools, kolks), on tributaries (tributary entrenchment), or directly in the channel (former channel entrenchment).

8.1. Longitudinal scour fields

These stream-lined microforms occur as swarms and are designated in this work as longitudinal scour fields (Fig. 8C). The maximum depth of the depression is 60 cm, the length is 200 m, and water depth ranges from 1 to 50 cm. The forms observed are either straight or meandering and according to Allen (1969), this is because whenever the critical stress is exceeded erosion gradually augments transforming small longitudinal scours into meandering ones. They are produced essentially by excess flow energy, which is further enhanced

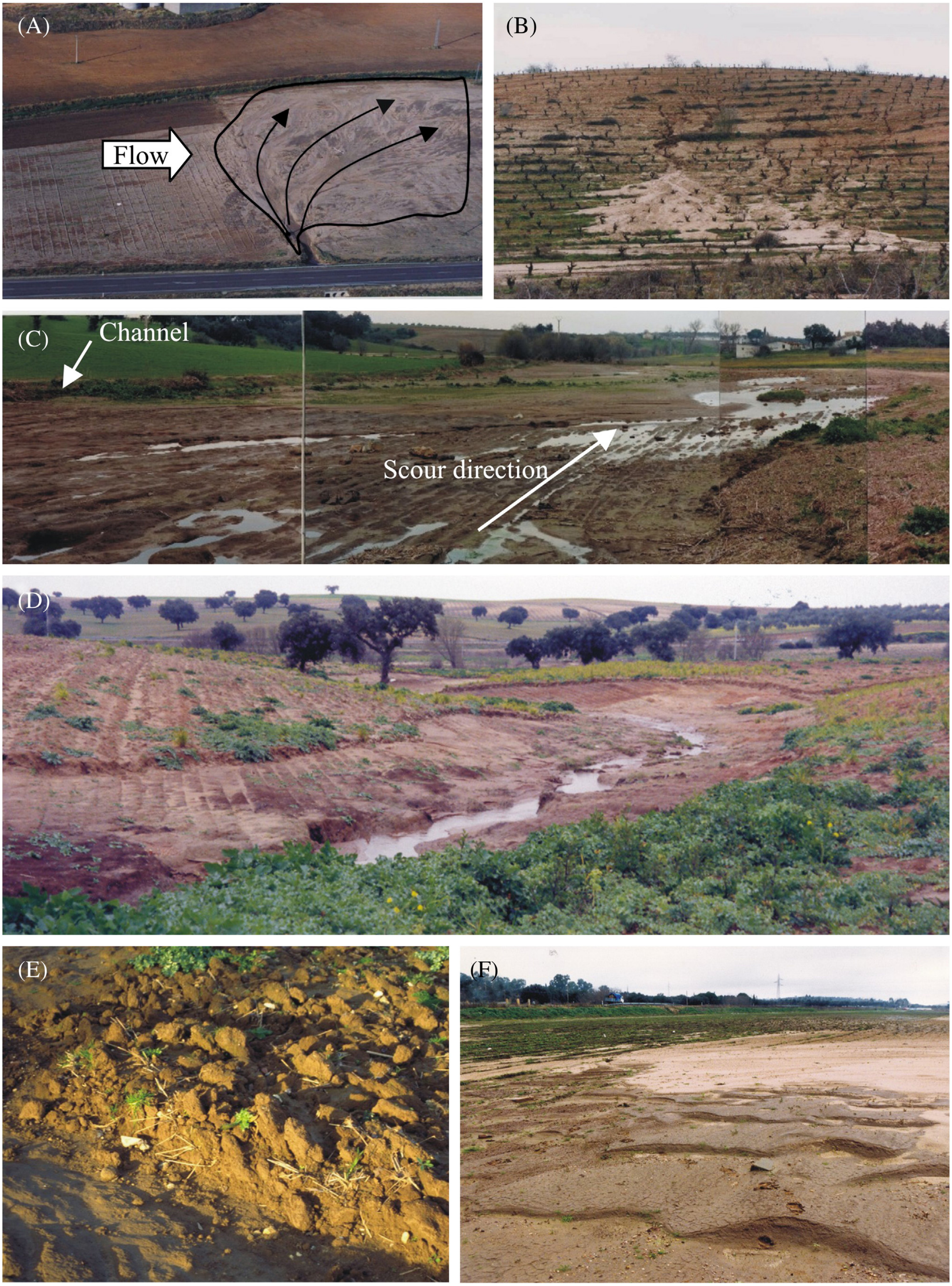

Fig. 8. (A) Asymmetrical alluvial fan developed from a lateral stream and elongated downstream by the main flow; (B) small alluvial fans related to piping processes on vineyards slopes; (C) longitudinal scour fields from to ploughing parallel to the main direction of flow; (D) entrenchment in a tributary stream at Romera reach; (E) mudball bar development; and (F) downstream edge of a sand flat.

by inappropriate farming practices such as deep ploughing parallel to the main direction of flow.

We believe that this form was generated during the early stages of the flood. Erosion intensified up until peak flow was reached; and then as the waters subsided, many furrows were filled with sandy deposits from longitudinal bars. The large extension attained by scour fields in all the studied reaches indicates the high bedload transference capability of the flood waters.

8.2. Lee hollows

Lee hollows form just downstream of obstacles related to elements destroyed and swept away by the floodwaters, such as blocks of brick fabric or large sections of fences. This suggests that the hollows were formed in the later stages of the flood, subsequent to overflow onto the plain and following the high energy peak flow that damaged buildings. In some cases, sand bars are covering the displaced block, which acquire a half-moon or horse-tail shape from the vortices caused by the obstacle.

8.3. Pools

Unlike the previous hollows, the main vortex occurs at a fixed point, and the pools deepen to as much as 60 cm reaching a maximum length 10 m. Their occurrence is always associated with obstacles of anthropic origin, such as roads, paths, and bridges. This form always develops downstream of the obstacle, with the more abrupt face upstream and gentle slope downstream. Finally, some of them may expand into longitudinal scours.

They are initiated in the highest flow stages of the flood when stream power is at a maximum. The erosional work, however, continue after the peak flow have subsided as long as there is water circulating over the obstacle because a waterfall is created enhancing the erosional capability of the flow.

8.4. Tributary entrenchment

This process has occurred preferentially in the upper part of the basin where tributary watersheds have undergone considerable alteration from farming. In some cases, the tributary channels have disappeared as a result of artificial earth remobilization. During this exceptional rainfall event, many tributaries recovered their channels, by incision to depths as high as 30–40 cm (Fig. 8D). The sediment produced by tributary entrenchment was largely accumulated in fans and bars.

8.5. Former channel entrenchment

On several reaches, the former channel (which can be seen in the aerial photographs from 1956), has been reactivated and entrenched showing hollows not associated with obstacles. Because of the recent anthropic changes on the river sinuous stretches had been cut off by channelization works and infilled. During the flood, entrenchment or reoccupation in artificially abandoned channels occurred where the substrate was least cohesive. The sequence of formation is indicated in Fig. 9 for reach 3.

9. Stability conditions of the morphosedimentary features and discussion

In order to produce some results on the most important variables that condition hydrologic conditions under which the morphosedimentary features form and remain preserved, HEC-RAS hydraulic modelling results for flood peak discharge have been taken into consideration. Three reaches (Fig. 1): Romera (site 5), Cansini (site 3) and Galache (site 1) were selected based on their landform variety. Final results are shown in Table 2. Differences between flood water level according to flotsam and to the calculated maximum discharge were 34 and 44 cm using Chow's and Cowan's roughness values respectively. If a reliability analysis is run on the flotsam measurements, the difference may be reduced to 26 cm (Table 2; Fig. 10).

The modelling provides quantitative data on the most important hydraulic variables for the different morphosedimentary features allowing us to derive a number of significant conclusions about the flood. The considered variables were water depth, velocity, shear stress, and stream power. Morphosedimentary maps of the three studied reaches and HEC-RAS hydraulic output data were used to calculate the range of hydraulic conditions within which features are formed and preserved.

The results (Table 3) suggest that depth is not a limiting factor for the preservation of features after the flood. Some present a wide range of depths, up to 140 cm for longitudinal sandy bars and 150 cm for crevasse splays. In both cases, the maximum depth threshold is high, implying that the resistance of the feature to erosion by water declines. Alluvial fans on the floodplain remain stable under a water flow <1 m deep. Erosive forms show the highest formation depth values, between 100 and 150 cm for scours; while former channel entrenchment attains maximum depths of 170 cm.

Velocity is the most significant factor in the formation of sedimentary or erosional features (Table 3; Fig. 11). The threshold between the development of erosional and depositional features has been established at around 1 m s^{-1}, although this limit is diffuse. In longitudinal sandy bars that have not been destroyed after flooding, the maximum value is 1.1 m s^{-1}, although in most cases this limit is less than 0.9 m s^{-1}. In crevasse splays, thresholds are similar (<0.9 m s^{-1}), but alluvial fans display lower range, between 0.7 and 1.1 m s^{1}. Erosional features require the highest velocity, but that does not indicate the moment of formation. Scours and former channel entrenchment features from in high velocity areas (between 1 m s^{-1} and 1.67 m s^{-1}).

In relation to shear stress there is a clear threshold between sedimentary and erosional features developed on the floodplain. Longitudinal bars withstand a shear stress range of 9 to 47 N m^{-2}, with values most commonly around 20 N m^{-2}; crevasse splay values tend to be above 16 N m^{-2}, with a maximum of 31 N m^{-2}, and alluvial fans present similar values between 15 and 39 N m^{2}. In the case of erosional features, shear stress values can be as high as 93 N m^{-2} and most commonly over 30 N m^{-2}; and in former channel entrenchments, they are over 35 N m^{-2}.

The last of the variables considered, stream power, presents a similar distribution for erosional features (22 and 152 W m^{-2} for scours, and slightly lower for former channel entrenchment, 36–69 W m^{-2}) and sedimentary features (10–38 W m^{-2} for fans, 0.8–29 W m^{-2} for crevasse splays, and 15–55 W m^{-2} for longitudinal bars).

For the peak flood (at Calamon and Rivillas confluence), we have estimated a maximum stream power of 923 W m^{-2} and mean values of 348 W m^{-2}. The unit energy expended, however, was 22600×10^{3} J, which results high when compared to the values analysed by other authors (Costa and O'Connor, 1995; Magilligan et al., 1998). Extreme geomorphic impact or effectiveness may be achieved either by high stream power and unit energy expenditure (Jarrett and Costa, 1986; Costa, 1994) or by low stream power but a long lasting peak flow on the hydrograph (Osterkamp and Costa, 1987). As a result, we may conclude that the energy expenditure values for the Rivillas flood are high compared to those of others with larger peak discharge and longer duration.

Our conclusions should be seen as a first approximation to feature characterization, relying on descriptive and interpretation aspects. In fact, the original goal when we undertook the analysis of the morphosedimentary features was to infer practical information that

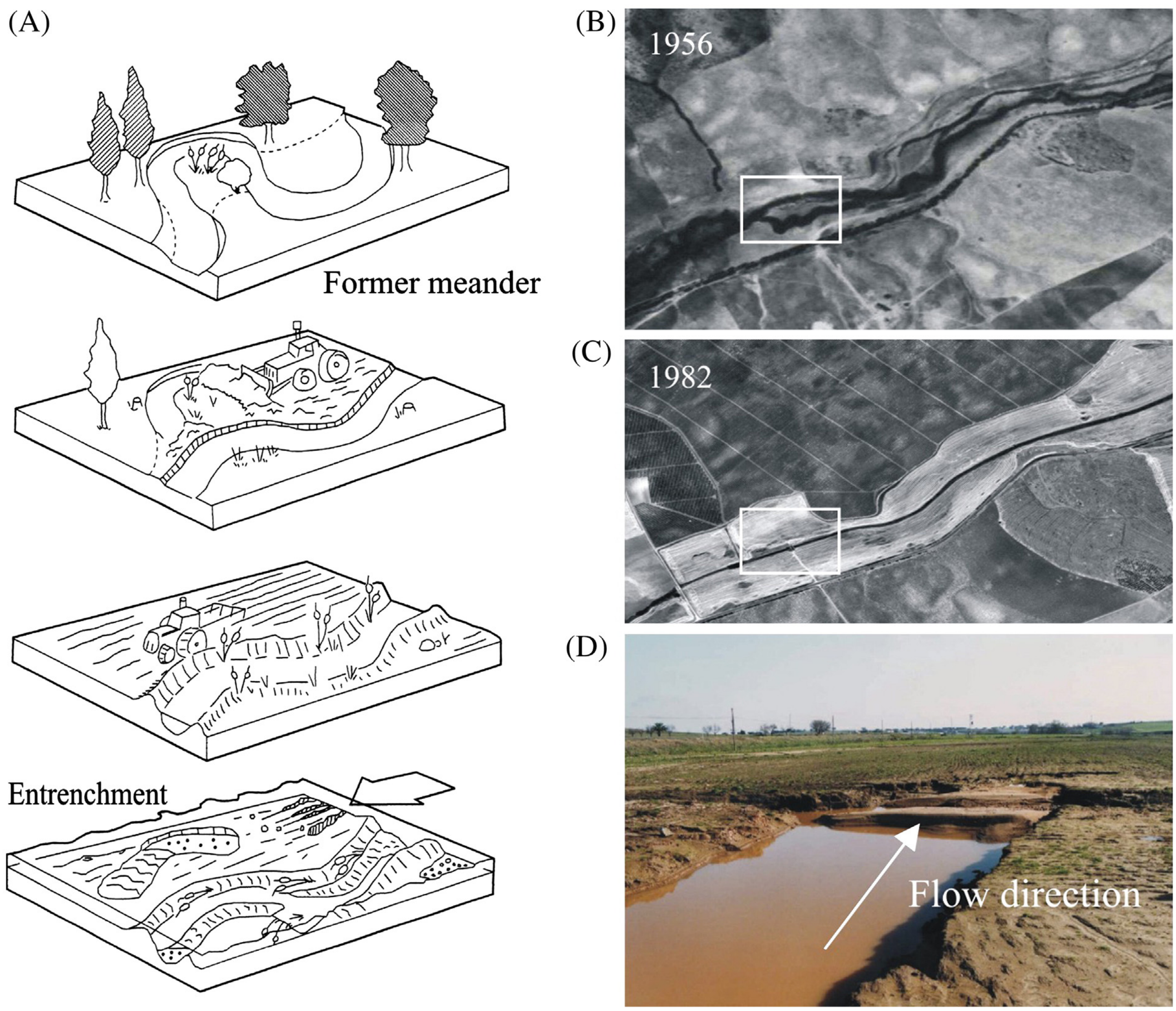

Fig. 9. Former channel entrenchment evolution (Cansini site). (A) Development of a channel entrenchment from an obliterated sinuous channel; (B) 1956 sinuous channel; (C) 1982 straightened channel; and (D) entrenched channel after the 1997 flood event.

could help us to gain a better understanding of flood evolution and hazards. The identification of so many peculiar, or at least hitherto unreported, features prompted investigation of their genetic significance and comparison with modelling results, (initially hydraulic modelling was undertaken only to establish flood discharge parameters).

These results are only preliminary as HEC-RAS is a one-dimensional hydraulic model with which only three mean values can be obtained for each section: in this cases channel, right bank, and left bank. Therefore, the estimated conditions and stability fields cannot be considered to be well constrained from our data. Also, the real scale of the variables is too large for estimation of small features such as linear and digitated levees, pools, etc. Moreover, due to scale limitations, the actual value of variables for small features may differ considerably from those obtained by means of the hydraulic modelling.

An exhaustive initial data collection with modelling of specific features would supply far more information and with a higher accurateness than we obtained. More detailed mapping combined with depth analysis would also make possible to establish sedimentation–erosion rates for a more quantitative balance. A better section knowledge, such as the one offered by three-dimensional models would be important for more precise variable adjustment.

10. Conclusions

Human interference is considered to be one of the main factors involved in the described development of the morphosedimentary features. Land use changes and anthropic structures produce changes in runoff coefficient, sediment supply and erosional processes in the

Table 2
Differences between flotsam height and the one obtained from both roughnesses considered options.

Site	Average difference (m)		Discharge (m^3 s^{-1})
	Cowan	Chow	
Site 5	0.58	0.53 (0.43*)	156
Site 3	0.33	0.23 (0.21*)	180
Site 1	0.42	0.26 (0.15*)	300
Rivillas (average)	0.44	0.34 (0.26*)	–

Results marked with an asterisk (*) are considered reliable.

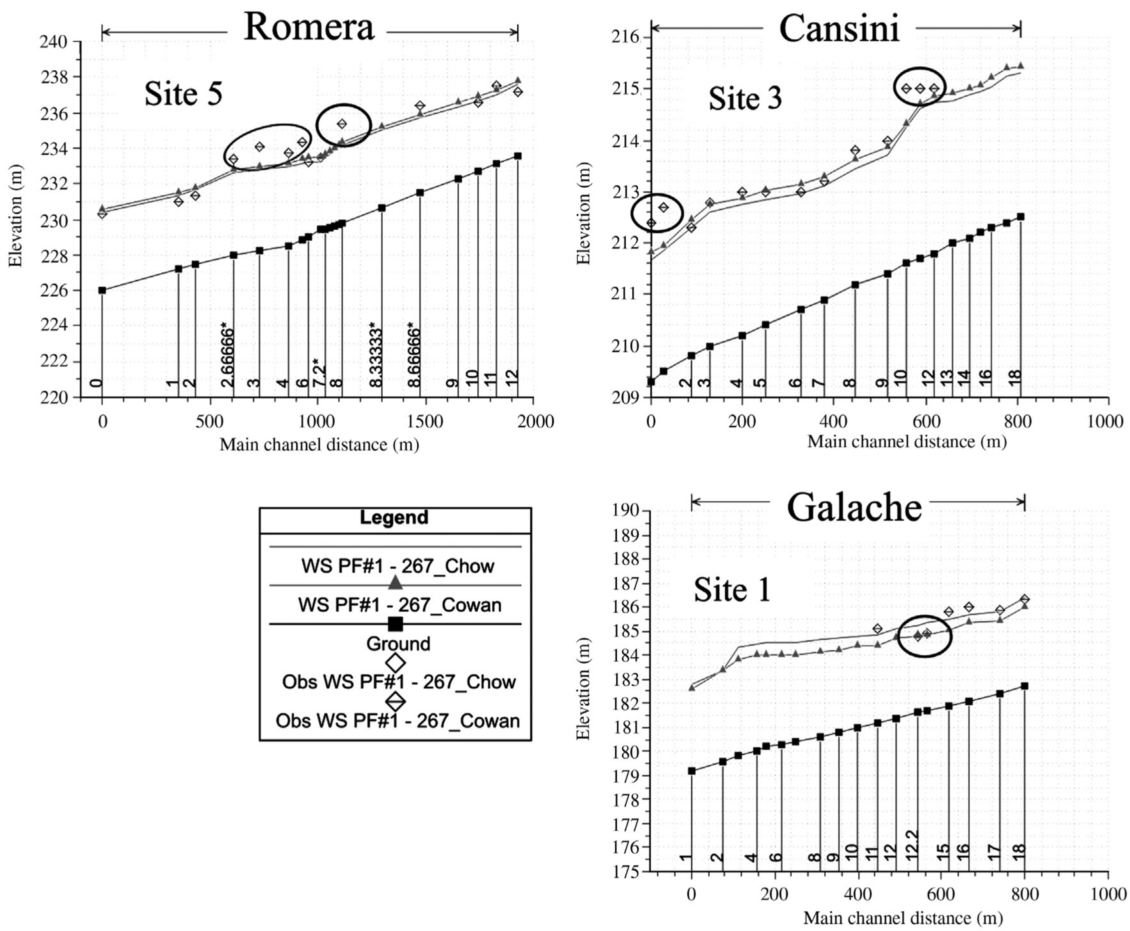

Fig. 10. Adjustment of roughness values in relation to flotsam data. Values that consider offering possible flow perturbation are marked with a circle.

channel and floodplain enhancing the flashy character of the flood and its severity (capability to cause damage). There is a negative balance in basin sedimentary budget, and erosive features are dominant over depositional ones.

The study of some features has yielded detailed information about water depth, flow velocity and other variables that are necessary to understand flood evolution. Sand flats form under low flow regime and shallow water depth. Longitudinal bars are sediment accumulation zones and adopt a sinusoidal shape on the floodplain, following flow lines. The coarser material in these bars is related to human activity, as are bars of mudclast, both occurring from excess energy whenever local conditions are favourable. Semilunate bars define a marginal position on the floodplain and imply flow diversion, as do shadow bars. Crevasse splays indicate remobilization of material, but in a short time span because shapes are preserved. Digitated and linear levees yield information about the start and end of the flood. Fans show that slopes are the main source of sediment and the

Table 3
Variables calculated for the three analysed reaches.

Feature		Reach	Water depth (cm)	Velocity ($m\ s^{-1}$)	Shear stress ($N\ m^{-2}$)	Stream power ($W\ m^{-2}$)
Bars and splays	Longitudinal sand bars	Site 5	50–100	0.4–0.9	9–40	4–33
		Site 3	100–140	0.8–1	21–33	18–34
		Site 1	60–140	0.7–1.1	19–47	15–55
		Range	60–140	0.4–1.1	9–47	4–55
	Crevasse splays	Site 5	<150	0.6	16.5	11
		Site 3	30–100	0.2–0.9	4–31	0.8–29
		Range	30–150	0.2–0.9	4–31	0.8–29
Alluvial fans		Site 5	<100	0.7–1.01	14.9–37.3	10–38
		Site 3	<30	0.9	39.2	37
		Site 1	<30	0.95	29.1	28
		Range	<100	0.7–1.01	15–39	10–38
Erosional features	Longitudinal scour fields	Site 5	150	1.37–1.67	81–93	120–152
		Site 3	100–145	1–1.42	31–76	32–108
		Site 1	130	0.68–1.2	17–57	22–71
		Range	100–150	0.68–1.67	17–93	22–152
	Former channel entrenchment	Site 5	170	1.1	58.7	69
		Site 3	120	1	35.4	36
		Range	120–170	1–1.1	35–58	36–69

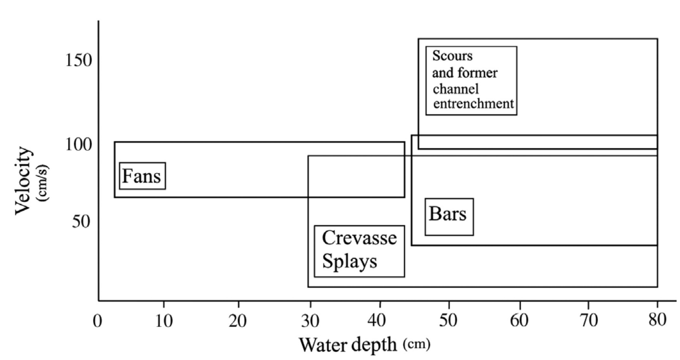

Fig. 11. Stability fields for velocity and water depth obtained for some features by modeling with HEC-RAS.

abundance of these reveal the impact of basin land use changes in the basin. These sediments preserve the sequence of events in the flood stages.

Erosional features were abundant and widely distributed although not very diversified. In almost all cases they are related to human activities or structures and reveal the high energy expenditure. Tributary entrenchment reflects the landform recovery after human induced obliteration. Similarly former channels entrenchment is indicative of the capacity of fluvial systems for self-adjustment, as they try to recover their original morphology channel pattern favouring more effective energy dissipation.

The analysis of stability variables shows a clear differentiation between erosional and sedimentary features in the floodplain. The latter indicate the threshold of stability of a feature on the floodplain, especially velocity, shear stress, and stream power. Depth, however, is not a limiting factor for feature preservation.

The identification of some features can improve our knowledge about attained conditions on the floodplain and has also an applied interest. Flood hazard mapping should be based not only on the area submerged by the flood and the water depth, but also on its velocity, shear stress or stream power.

Mapping of flood prone areas is usually based on the delineation of areas subject to inundation during flood events with a particular return period. This strategy which is very dependent on statistical approaches and on the quality of hydrological information, does not consider the specific risk at a certain location.

Changes in channel pattern and straightening, together with artificial fil1ing of channels that acted as subsidiary flood pathways, are responsible for altering the hydraulic characteristics of the floods and magnifying their potential for valley-floor erosion. The lessons learnt from this flood have implications for the evaluation of potential hazards and identification of risk locations. These are the areas in which the application of mitigation measures, either of preventive or corrective nature, should be of top priority.

As Millar and Parkinson (1993) indicate it may be more useful the information on actual floods and particular kinds of hazards, than predicting the areas that might be affected by a theoretical flood with a certain return period.

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