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FLOW AND SEDIMENT CONNECTIVITY IN SEMI-ARID LANDSCAPES IN SE SPAIN: PATTERNS AND CONTROLS

Miguel Marchamalo[1]*, Janet M. Hooke[2], Peter J. Sandercock[3]
[1]*Department of Land Morphology and Engineering, Technical University of Madrid, ETSI Caminos, Canales y Puertos, Madrid 28040, Spain*
[2]*Department of Geography and Planning, University of Liverpool, Liverpool L69 7ZT, UK*
[3]*Jacobs, 80A Mitchell Street, PO Box 952, Bendigo, 3552, Australia*

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ABSTRACT

Much of the water and sediment fluxes in semi-arid catchments are found to be highly concentrated in localized pathways. Identifying the location of these pathways in the landscape is important for management and restoration. Measures can then be targeted so as to minimize the potential for erosion and sediment flux along these pathways. A method of repeat field mapping of flow and sediment pathways suitable for Mediterranean catchments is presented. Several small catchments in Cárcavo basin, SE Spain, differing in topographic and land use characteristics, were monitored under several events. Morphometric properties of pathways were analysed and compared with rainfall characteristics. Number and length of pathways varied with rainfall characteristics and also antecedent conditions. In low rainfall events, runoff sources and main pathways were disconnected, but in a larger event, the network of pathways became fully connected. The pathway patterns showed that man-made lines such as terrace embankments and tracks have a major influence on sediment connectivity. Microtopographic factors, soil moisture and the presence of vegetation are highly influential on pathways and the frequency of water and sediment fluxes. Runoff and erosion hotpots for the development of pathways were identified, which should be targeted for mitigation and restoration measures using vegetation. The relevance of local scale factors emphasizes the importance of repeat field observations to understand connectivity and pathways development in the landscape.

KEY WORDS: runoff; soil erosion; hotspots; landscape linkages; vegetation; desertification; geographic information systems; Mediterranean

INTRODUCTION

Most climate change scenarios predict worsening conditions for desertification in the Mediterranean region, already vulnerable to climate variability, with less and more irregular rainfall and higher risk of extreme events expected (IPCC, 2007). This will reduce agricultural productivity and lead to further land abandonment (Olesen & Bindi, 2002). Adaptation strategies to climate change require more sustainable land management, increasing soil conservation and reducing the vulnerability to land degradation (IPCC, 2007).

Several studies quantified the erosion and sedimentation processes at plot, hillslope and catchment scale in the Mediterranean region. Martínez-Mena *et al.* (1998), Cerdà (2001), Romero-Díaz (2002), Calvo-Cases *et al.* (2003), Boix-Fayos *et al.* (2005) and Cerdà *et al.* (2010) provided extensive reviews of the work in the Mediterranean basin and more specifically in SE Spain. Cammeraat (2002, 2004) analysed the possibilities for up-scaling results in semi-arid landscapes, finding that linear up-scaling from fine to broad scale is impossible, as many thresholds and nonlinear processes are involved. The structure of hillslope drainage networks differs from the structure of channel networks, as hillslopes are not scale invariant (Moody & Kinner, 2006). Martínez-Mena *et al.* (1998) showed the highly variable nature of the hydrological response in semi-arid environments. Responses of hillslope drainage networks in semi-arid landscapes vary depending on soil physical properties and soil-moisture distribution in the landscape.

The patchy structure of vegetation, as an adaptation to semi-arid climate, plays a crucial role in soil processes. Puigdefabregas (2005) presented a review of the role of vegetation patterns in structuring runoff and sediment fluxes in drylands at both individual plant clumps and patch scale. Vegetation patches present lower runoff and sediment yields, and higher soil moisture than bare areas (Ludwig & Tongway, 1995; Puigdefabregas & Sánchez, 1996; Cerdà, 1997). Bautista *et al.* (2007) suggested that plant spatial patterns, soil crust and functional diversity are interrelated and strongly influence hydrological response in semi-arid landscapes. The loss of cover and increase in vegetation patchiness have been related to soil degradation processes (Kakembo *et al.,* 2012; Kröpfl *et al.,* 2013).

Connectivity can be seen as the process/es entailing a transfer of matter, energy and/or genetic information within or between elements of the landscape at different scales (Pringle, 2003; Freeman *et al.,* 2007; Tetzlaff *et al.,* 2007). The concept, originated in ecology (e.g. Ward & Stanford, 1995), is widely used in hydrology, geomorphology and erosion and sedimentation research, at scales ranging from reaches

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* Correspondence to: M. Marchamalo, Department of Land Morphology and Engineering, Technical University of Madrid, ETSI Caminos, Canales y Puertos. Madrid 28040, Spain.
E-mail: miguel.marchamalo@upm.es

to basins (e.g. Harvey, 2000; Western *et al.,* 2001; Brierley *et al.,* 2006; Warner, 2006; Bracken & Croke, 2007; Fryirs *et al.,* 2007). In the context of landscape, we can identify linkages (pathways) and discontinuities as breaks of slope and other temporal and spatial buffers (Warner, 2006).

In a geomorphologic context, hydrological and sediment connectivity have been analysed separately, although they are closely related (Baartman *et al.,* 2013). Hydrological connectivity has been widely studied and, thus, defined under different approaches: (i) soil-moisture connectivity; (ii) flow-process connectivity; (iii) terrain connectivity; (iv) modelling; and (v) indices of hydrological connectivity (Ali & Roy, 2009; Bracken *et al.,* 2013). The concept of sediment connectivity means the physical linkage (transfer) of sediment and the potential for a specific particle to move through the system (Hooke, 2003). This entails understanding the local sediment sources and the mechanisms, conditions, routes and distances of transport. Sediment detachment and sediment transport can both be controlled hydrologically, although in some cases may be independent from hydrology (bedrock landslides, uplift, aeolian and anthropic processes) (Bracken *et al.,* 2014).

Several approaches have been proposed to measure connectivity at different scales (Western *et al.,* 2001; Lane *et al.,* 2004, 2009; Imeson & Prinsen, 2004; Bracken & Croke, 2007; Mueller *et al.,* 2007; Borselli *et al.,* 2008; Meerkerk *et al.,* 2009; Antoine *et al.,* 2009), and others have recognized structural and functional components and factors (e.g. Fryirs *et al.,* 2007; Lexartza-Artza & Wainwright, 2009, 2011). The consideration of hydrological connectivity improves the modelling of runoff (Mueller *et al.,* 2007) and coarse sediment delivery (Reid *et al.,* 2007), whereas the inclusion of gully factors improves sediment yield modelling (Verstraeten *et al.,* 2003). Baartman *et al.* (2013) explored the relationships between connectivity and landscape complexity through modelling of different landscape configurations subjected to rainfall simulation in the LAPSUS model.

Biogeomorphic approaches indicate that vegetation plays a crucial role in connectivity processes, at landscape and channel scales (Sandercock & Hooke, 2006, 2010, 2011). Human-made geodiversity as in terraced croplands (Ore & Bruins, 2012) decreases connectivity if they are adequately maintained, whereas degradation induced by fire (Lasanta & Cerdà, 2005), badly maintained terraces, ditches, tracks and roads (Croke *et al.,* 2005; Monsieurs *et al.,* 2014; Tarolli *et al.,* 2014), non-sustainable agricultural practices (Haregeweyn *et al.,* 2013) and general human population pressure (Prokop & Poręba, 2012) tend to increase connectivity. Thus, the analysis of connectivity provides an integrated approach for the study of complex systems (Lexartza-Artza & Wainwright, 2009). Changing patterns of connectivity, mainly increased pathway lengths, have been related to desertification (Okin *et al.,* 2009; Wainwright *et al.,* 2011).

Extensive field surveys combined with expert knowledge of the catchment are key elements for building robust hydrological and sediment delivery models (Keesstra *et al.,* 2009). Connectivity concepts need to be appropriately grounded by field investigations to support the generation of realistic 'visions' and prediction mechanisms (Brierley *et al.,* 2006). Arid and semi-arid ecosystems are adapted to episodic rainfall events (Noy-Meir, 1973) with high intra-annual and inter-annual variability. Understanding the dynamics of change in connectivity requires repeated mapping, as the comparison between maps from different times would show whether connectivity remains stable, is dynamic or is propagated (Hooke, 2003).

Field-validated connectivity models are essential for identifying restoration 'hotspots'. Hotspots are areas that, unless properly managed, can be severely eroded (or receive excessive sedimentation) and begin a process of export of unwanted sediment. Generally, hotspots can be managed locally by, for example, protecting them with vegetation or, at landscape scale, reducing the amount of runoff and sediment from upslope areas. Most of the sediment is lost from these hotspots in the landscape; therefore, once they are identified, they can be targeted for restoration (Hooke *et al.,* 2007). Consequently, the connectivity approach is essential for identifying hotspots and, thus, developing sustainable strategies for land degradation control using vegetation, with a hierarchically scaled approach from land units to catchments (Hooke *et al.,* 2007; Hooke & Sandercock, 2012). Previous mapping methodologies for main channels (Hooke, 2003) were extended (Sandercock & Hooke, 2010), but more field-based information is needed about the actual pathways of sediment movement, the position of sources and stores and the influence of spatial arrangement of land uses (Lesschen *et al.,* 2008).

This research contributes to filling these gaps by developing methods of mapping and by providing further evidence of temporal and spatial variability in connectivity to increase understanding of patterns and dynamics. Such data are also needed to validate models of connectivity. The objectives of this research are to (i) develop a methodology for mapping and characterizing flow and sediment connectivity that will aid in targeting restoration hotspots in semi-arid landscapes; (ii) evaluate and quantify connectivity for different landscape settings under a range of rainfall events; and (iii) evaluate factors influencing flow and sediment connectivity at sub-catchment scale.

METHODS

Study Area

The experiments were set up in Cárcavo basin, Murcia, SE Spain (Figure 1), selected as a representative area prone to land degradation and desertification in terms of climate (semi-arid Mediterranean), land use (marginal crops and rangeland) and parent material (marls and gypsum deposits). Cárcavo is a 30-km^2 catchment of altitude 220–850 m, average annual rainfall of 300 mm and potential evapotranspiration of 900 mm (Lesschen *et al.,* 2007). The geology consists of peripheral Jurassic limestone and dolomite ridges and central Cretaceous and Miocene marls and Keuper gypsum deposits. Most soils in the area are thin (Leptosols),

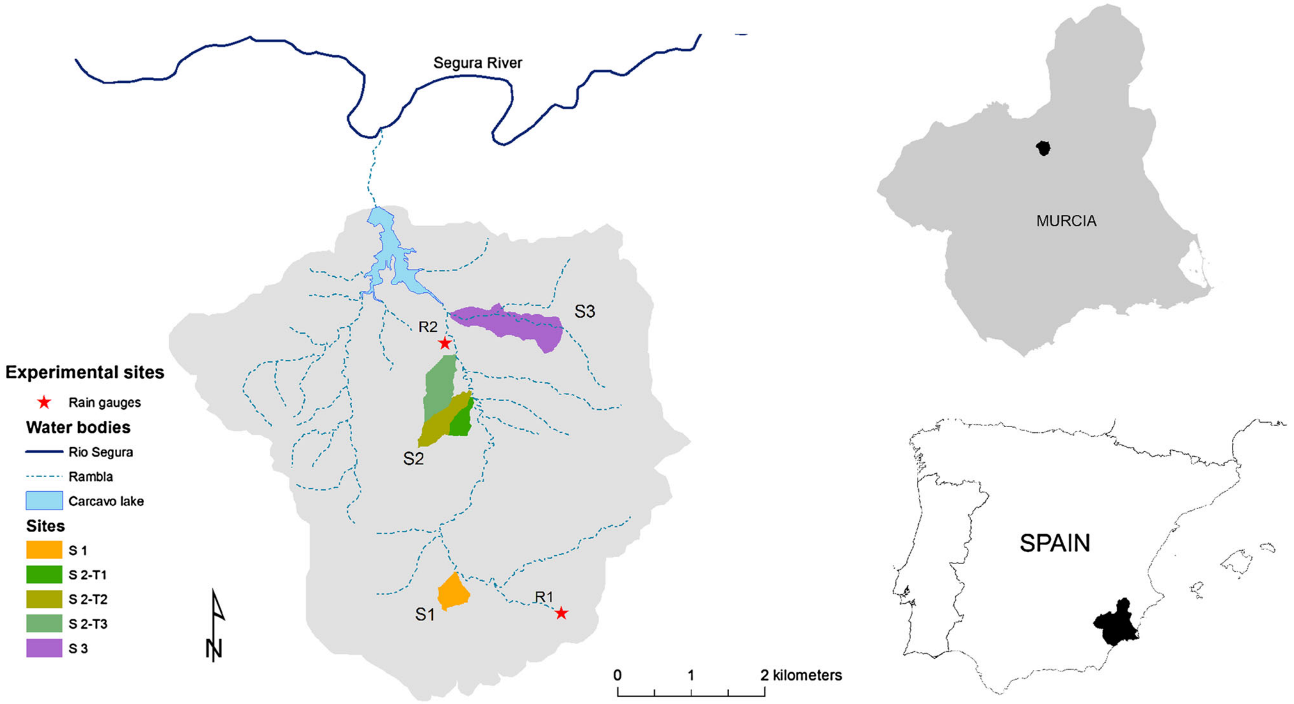

Figure 1. Experimental sites in Cárcavo basin, Murcia, SE Spain. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

weakly developed (Regosols) and mainly characterized by their parent material (Calcisols and Gypsisols) (Lesschen *et al.,* 2007).

Land use patterns in the study area consist of rainfed crops (cereals, vines, olive and almond trees), abandoned land, reforested land and semi-natural vegetation. Large reforestations with pine (*Pinus halepensis* Mill.) date from the 1970s as part of soil conservation programs. Some almond and olive fields in the central part are under irrigation. During the last few decades, parts of the non-irrigated agriculture have been abandoned and are under different stages of secondary succession (Lesschen *et al.,* 2007).

Three sub-catchment scale sites between 10 and 54 ha in size were chosen within the Cárcavo catchment for detailed connectivity mapping (Figure 1). They were all located in headwaters, over marly substrate, and presented different landscape and land use configurations to evaluate influences on connectivity pathways.

Site 1 (S1) is a small agricultural catchment (14 ha) located in the upper Cárcavo basin, with abandoned lands in headwaters and cropped olive and almond trees over conglomerates and marls. Site 2 (S2) comprises a set of three small tributaries: T1 (10 ha), T2 (21 ha) and T3 (23 ha) in the left bank of lower Cárcavo rambla over marls. All of them present mature terraced *P. halepensis* Mill. reforested lands in the headwaters. T1 and T2 are all in reforested land, whereas T3 presents a mixture of semi-natural vegetation (*Stipa tenacissima* L., *Rosmarinus officinalis* L. and *Brachypodium retusum* (Pers.) Beauv.) and olive–almond orchards in the lower parts. Site 3 (S3) (49 ha) comprises the medium and lower reaches of a right bank tributary of lower Cárcavo rambla. It presents a mixture of abandoned

Table I. Rainfall events during the studied period

Station	Parameter (mm)	5 Apr 8 Apr 2005	6 Jan 10 Jan 2006	6 Apr 28 Apr 2006	6 Sept 11 Sept 2006	6 Nov 8 Nov 2006
R1	P	19·5	26·2	*21·3*	23·0	39·2
Upper catchment	I_{60}	15·7	11·3	*20·3*	20·3	17·9
	I_{30}	13·1	6·1		18·8	18·6
	I_{10}	9·7	2·9		12·1	10·1
	P30d	30·1	16·9	*12·8*	2·0	127·0
R2	P	22·7	20·4	*21·3*	7·4	*39·2*
Lower catchment	I_{60}	18·4	9·4	*20·3*	6·2	
	I_{30}	16·3	6·0		5·4	
	I_{10}	10·3	2·4		2·4	
	P30d	23·7	13·4	*12·8*	0·0	

Note. R1 and R2 locations in Figure 1. Rainfall (P), 1-h maximum rainfall (I_{60}), 30-min maximum rainfall (I_{30}), 10-min maximum rainfall (I_{10}) and 30 days' cumulated rainfall (P30d). In April 2006 and November 2006, rain gauges failed, and data (in italics) were obtained from the nearest stations located in Cieza (www.aemet.es) and Abarán (http://siam.imida.es).

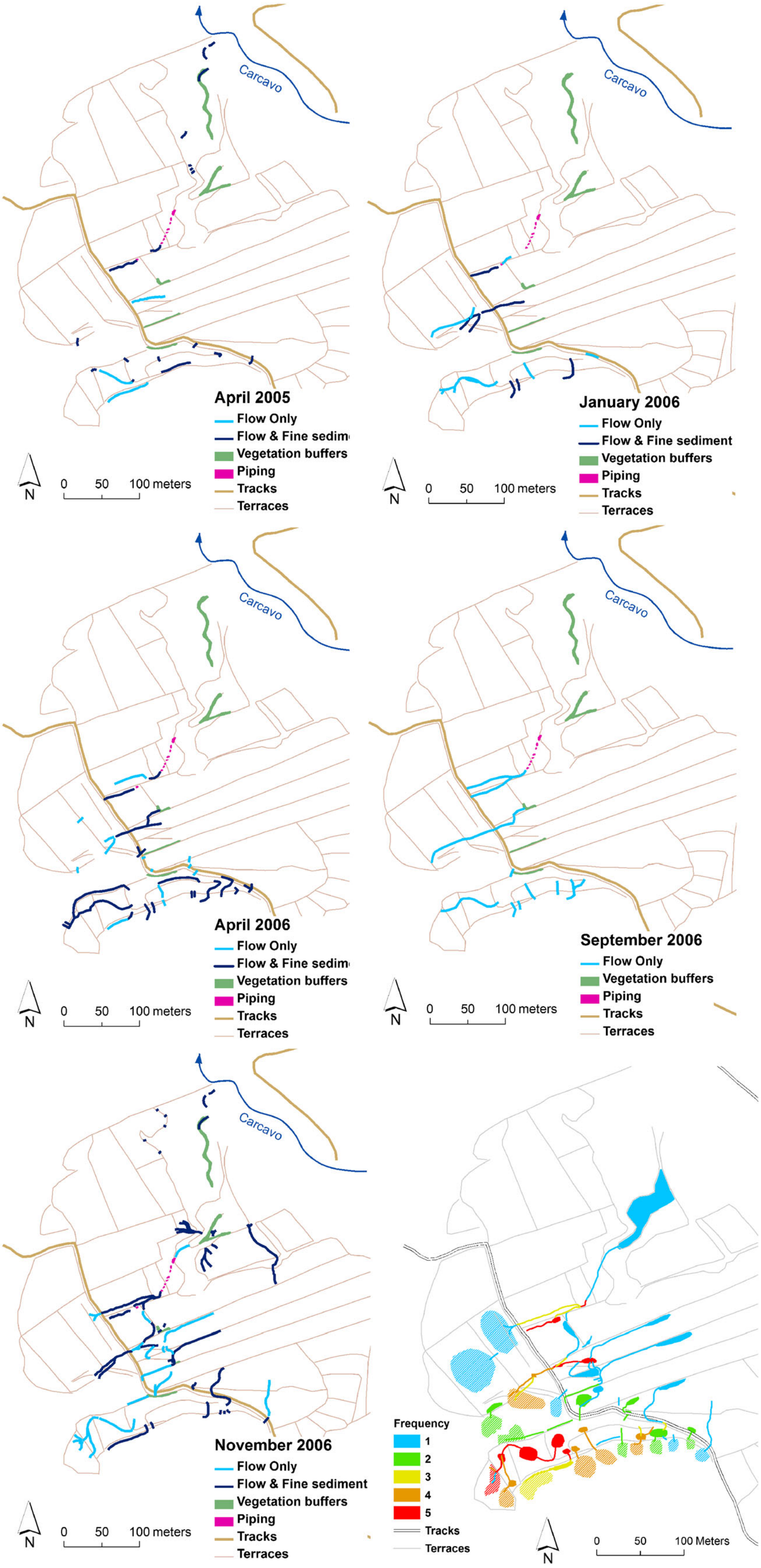

Figure 2. Repeated connectivity assessment in Site 1 (S1) and frequency analysis. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table II. Morphological features of observed connectivity patterns in S1 site (Murcia, SE Spain) for a series of rainfall events

	Total length of connected pathways (m)			Number of connected pathway links		Average length of pathway links (m)	
	Flow only	Flow and sediment	Total	Flow and sediment	All	Flow and sediment	All
8 Apr 2005	154	250	404	9	11	28	37
10 Jan 2006	244	237	481	5	9	47	53
28 Apr 2006	347	455	802	15	23	30	35
11 Sep 2006	576	0	576	0	12		48
8 Nov 2006	702	583	1285	14	21	42	61

and cropped land with some reforested areas in the headwaters and steep areas adjacent to the main channel.

Experimental Approach

The experimental approach is based on the repeated monitoring of landscape linkages after different rainfall events. A three-step method is developed to map connectivity at the sub-catchment scale.

Active areas are classified into sources, pathway links and sinks. Sources are the areas where runoff is produced, and the associated erosion processes may begin (diffuse/sheet erosion). They are identified in the field just after rainfall events, seeking for the origin of landscape linkages. Pathway links are water and sediment transfer zones that link sources and sinks, whereas erosion and sedimentation processes may also occur within them. Sink areas are deposition zones where sedimentation processes dominate, such as fans, embankments, terraces, natural or man-made depressions, deposits, barriers, vegetation buffers and check dams. A protocol was defined for the visual identification of 'connected pathway links', classifying them into 'flow only' versus 'flow and sediment pathway links'. Flow-only connected pathways include overland flow and flow over previous formed rills with hydraulic power under the threshold for erosion initiation. These are detected by traces of wet soil and alignment of trash/leaves after events. Flow and sediment connected pathways are identified as those involving sediment erosion, transfer and/or deposition. Sediment is classified into fine (clay, silt or sand) and coarse (gravel, cobble or boulder).

Systematic repeat connectivity mapping uses fairly simple techniques and easily collected data. It examines outcomes in terms of geomorphology and sedimentology. It assumes

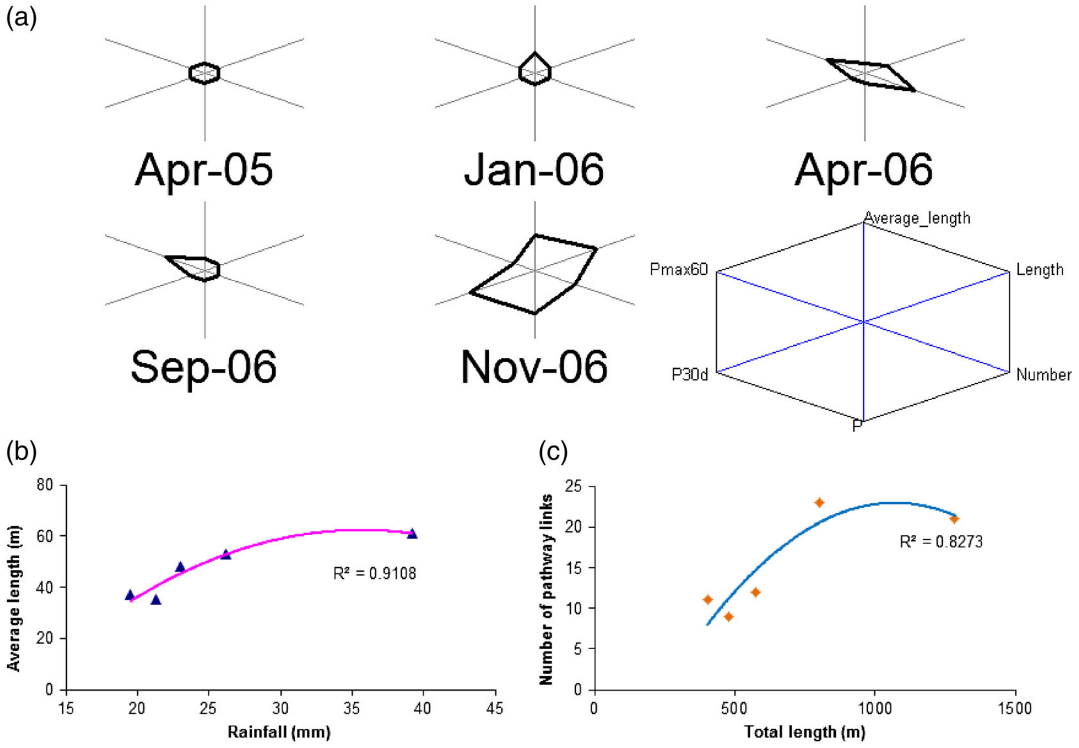

Figure 3. (a) Star plots showing the main characteristics of rainfall events and mapped pathway links in Site 1 (S1). Pmax60, maximum rainfall in 60 min; P, rainfall; P30d, cumulated 30 days' rainfall. (b) Number and average length of connectivity pathway links for five events in Site 1. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table III. Pearson correlation coefficients for a pairwise comparison of rainfall and connectivity characteristics in S1 site (dark grey and bold, $p < 0{\cdot}05$; light grey, $p < 0{\cdot}10$)

	Variables	Morphometry							External factor		
		Length of connected pathways			Number of connected pathways		Average pathway length		Rainfall		
Variables	Process	Flow only	Flow and sediment	Total	Flow and sediment	All	Flow and sediment	All	Rainfall (mm)	Max rainfall (60 min)	Rainfall (30 days)
Length of connected pathways	Flow only	1·00	0·23	0·79	0·04	0·48	0·35	0·65	0·73	0·55	0·58
	Flow and sediment		1·00	0·78	**0·95**	0·78	0·03	0.20	0·60	0·06	0·74
	Total			1·00	0·62	0·80	0·23	0·54	0·85	0·39	0·84
Number of connected pathways	Flow and sediment				1·00	0·81	−0·44	−0·13	0·32	0·19	0·55
	All					1·00	−0·26	−0·04	0·38	0·64	0·46
Average pathway length	Flow and sediment						1·00	0·86	0·62	-0·62	0·29
	All							1·00	**0·88**	-0·28	0·65

that certain processes and functions can be inferred from morphological and sedimentological evidence, being therefore truly geomorphological (Hooke, 2003). The three steps are:

(1) Base map survey (structural component). This step consists of mapping the distribution and pattern of different land uses for the area as well as the main topographic features related to field configuration that may contribute to or disrupt connectivity, such as tracks, tractor passes, agricultural terraces, embankments, protections, field limits, natural barriers, vegetation buffers and check dams. The base map survey is performed in the first field campaign using 1/5,000 maps to locate the aforementioned features with a handheld GPS.

(2) Systematic repeat connectivity mapping (functional component). The process of connectivity mapping involves the systematic remapping just after precipitation events, working from either the top of the catchment area or from the bottom of the network and distinguishing between relict features and those which formed during the recent event (fresh features). The position of all features is recorded and mapped using a GPS-integrated digital camera.

(3) GIS map production and analysis. Mapped information is input into a GIS database. Feature types are assigned by analysing the involved process: source (where flow initiates), overland flow (sheet runoff with no significant erosion), diffuse/sheet erosion, rill (small concentrated flow pathway), gully (actively incised pathway >30 cm deep), pipe (underground connection), headcut (head of an incision zone), breach (headcut on a broken section of a terrace or check dam), sink (area where pathways end and flow or sediment concentrate) and deposit (sink with sediment deposit in the landscape).

For each campaign, an activity map is produced, showing the recorded activity. A geomorphological map is produced, integrating all recorded activity and identifying sources, pathway links and sinks and main features, especially ‘hotspots’ where restoration efforts may be focused. Results for larger sites (as S2 and S3) were analysed at micro-catchment scale, using units delineated with ARCSWAT for ArcGIS with a threshold of 0·1 ha, based on 5-m contour topography and verified in fieldwork.

Once the GIS spatial database is created, a set of analyses is performed, comprising morphometric analysis of pathways (total connected length, number of connected pathway links and average pathway length), rainfall event characteristics (total rainfall, maximum rainfall in 60 min; antecedent cumulated 30 days) and frequency (times each feature was active, threshold conditions). A set of statistical tests is performed in order to check overall relationships among morphometric and rainfall variables using Statgraphics 5·0.

Rainfall Events

Experimental sites were monitored just after five rainfall events in the period from April 2005 to November 2007. Rainfall data were obtained from two instrumented data-logged rain gauges installed by the University of Amsterdam in

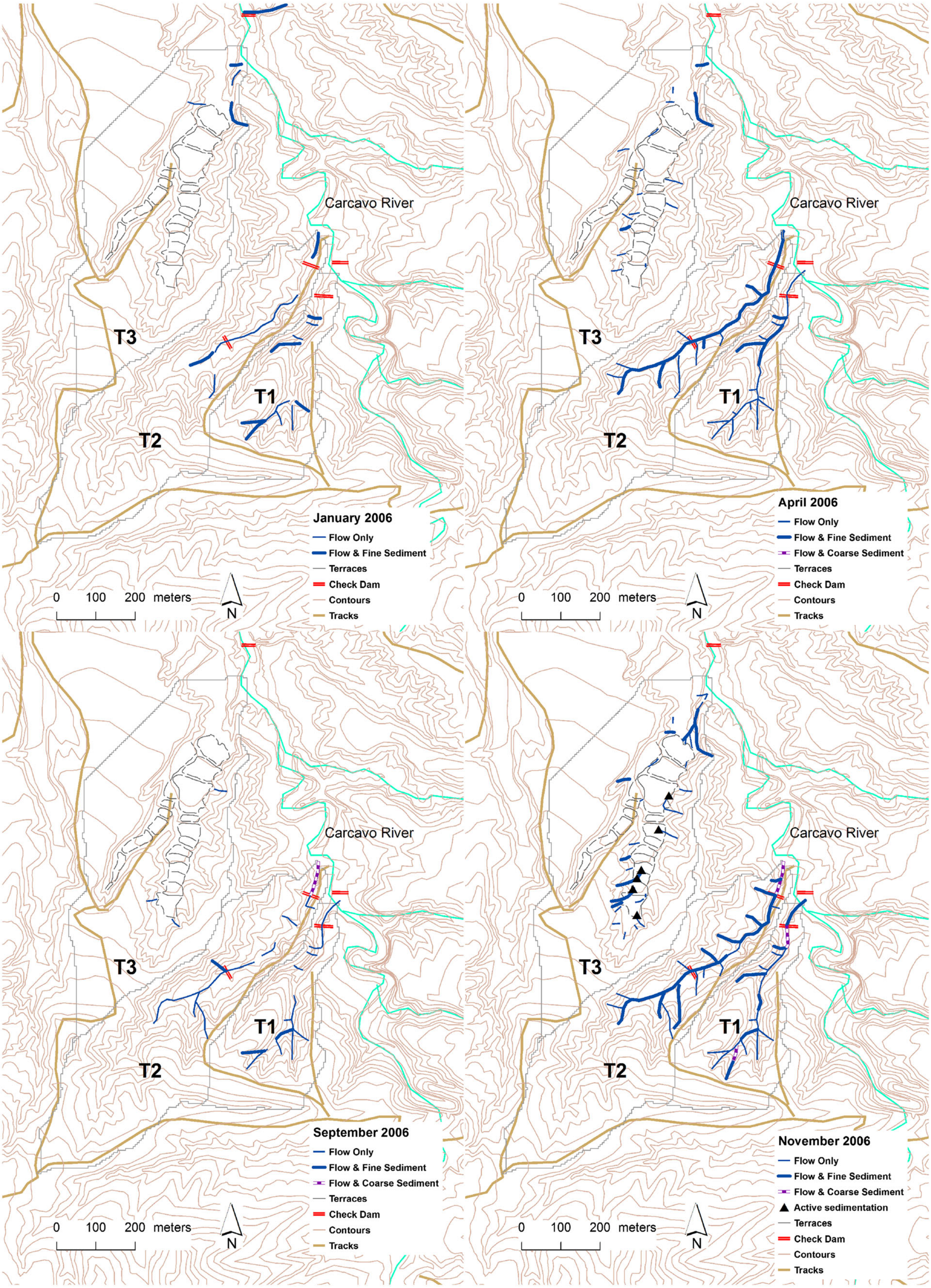

Figure 4. Connectivity patterns in Site 2 (S2) site after monitored events. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Cárcavo catchment, one in the upper part (R1) and the other in the lower part (R2). Table I shows the rainfall parameters for the monitored events. During 2005–2006, a total of 34 events were recorded over 5 mm, with 17 events over 10 mm and eight events over 20 mm (three of them in the period of 3–8 November 2006, so they were analysed together as November 2006 event). All events over 20 mm were mapped in the field, except for the 7 September 2005 event (30·1 mm) in which antecedent conditions were very similar to the mapped 12 September 2006 event.

RESULTS

Mapped Connectivity Patterns in a Small Agricultural Catchment: Site 1

Figure 2 shows the activity for each of the five rainstorms for S1, as mapped just after each event. In April 2005, after a rainfall event of 20 mm (maximum $15\,\mathrm{mm\,h^{-1}}$), there was evidence of erosion of the terrace banks by concentrated flow (rilling) and reactivation of previous bank failures. Sediments eroded from one terrace bank were deposited on the terrace immediately below. Runoff from the track contributed to more significant erosion along an established drainage line traversing an olive field (rill 35 cm wide, 10 cm deep and 10 m in length). Sediments were deposited behind the terrace wall, rather than transferred to the next terrace below. Piping and tunnel erosion were at an advanced stage of development in the lower part of the catchment. In January 2006, after a low-intensity rainfall event of 26 mm (maximum $11\,\mathrm{mm\,h^{-1}}$), mapped runoff and erosion pathways followed longer main drainage lines, with less activity on lateral sources than in April 2005. On the other hand, a comparable but more intense event in April 2006 (20 mm) activated many lateral sources, as well as main lines. The event in September 2006 was similar in size and intensity to those previously recorded but resulted in low soil detachment and movement, with almost no sediment redistribution.

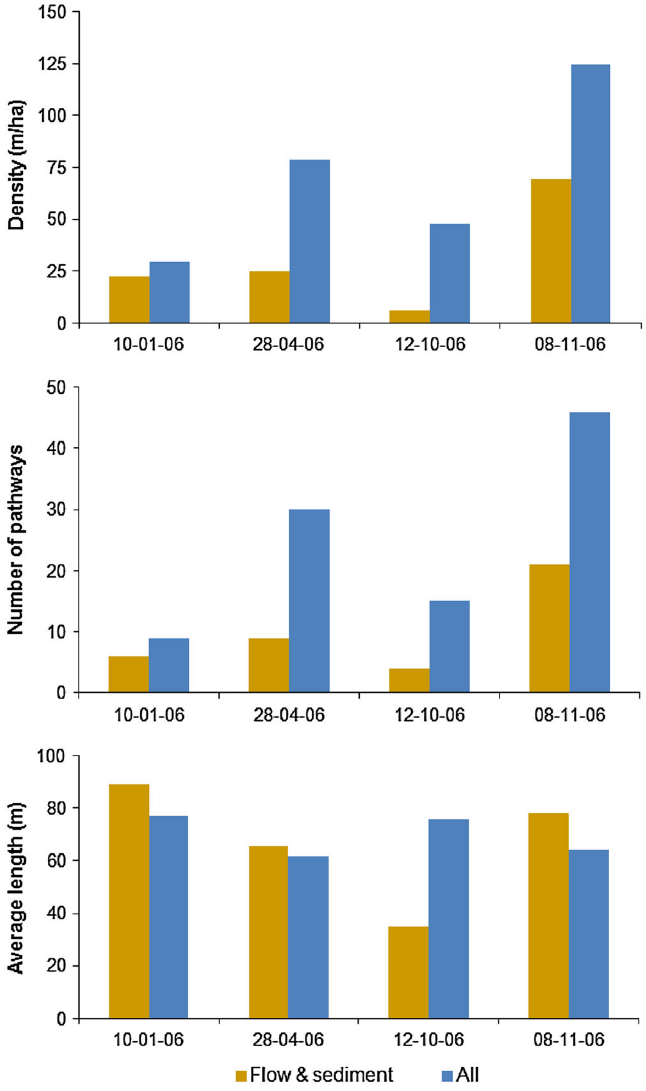

Figure 5. Analysis of density (a), number of links (b) and average length (c) of active pathway links in Site 2. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

During the November 2006 event (39 mm, with an antecedent precipitation of 122 mm in 7 days), significant sediment redistribution occurred, with the formation of new rills over the ploughed fields, resulting in relatively high overall flow and sediment connectivity. Runoff from agricultural tracks contributed to the formation of rills across the fields. Sediments were transferred to the next terrace below, rather than deposited behind the terrace wall. The piping and tunnel erosion in the lower part of the site showed significant reactivation. Table II presents the results of the morphological analysis of the connectivity pathway links for S1.

Figure 3a compares the footprint of recorded activity and rainfall parameters in terms of rainfall event characteristics (antecedent rainfall, intensity and total rainfall) and subsequent pathway features (total length, number of pathways and average length). The event on November 2006 (39 mm) overpassed a threshold of activity, with high antecedent rainfall, achieving a high degree of landscape connection, with a maximum in total length of connected pathways. Among the others, the one in April 2006 (20 mm) produced a high number of pathways. The event in September 2006 was preceded by a long dry period, which resulted in less hydrological connectivity and no sediment connectivity.

Correlation analysis (Table III) shows that there is a positive association between the total length and the number of pathways ($r=0{\cdot}80$), stronger in the case of flow and sediment pathways ($r=0{\cdot}95$; $p<0{\cdot}05$). The total length of all connected pathways is associated with the total and antecedent rainfall ($r=0{\cdot}85$ and $r=0{\cdot}84$; $p<0{\cdot}10$) but not so much to rainfall intensity (I_{60}; $r=0{\cdot}39$). The average length per linkage for all of them is associated with total rainfall ($r=0{\cdot}88$, $p<0{\cdot}05$) (Figure 3b).

Mapped Connectivity Patterns in Three Contrasting Tributaries: Site 2

S2 site comprises three main tributaries flowing SW–NE (Figure 4). Drainage is influenced by overall topography, and terraces in reforested and rainfed lands (T1, T2), but the effect of agricultural terraces is greater on Tributary 3 (T3). Several check dams influence connectivity in both the tributaries and the main channel. The lower check dam in T2 is collapsed at present, so flow and sediment pass through it, whereas the check dam in T1 is still efficient in trapping sediments.

Patterns of connected pathways for the monitored events are presented in Figure 4, and density, number of links and average length of active pathways in S2 micro-catchments for the monitored events in Figure 5. Micro-catchments in the untended terraced reforested headwaters of S2 T1 and T2 reacted very frequently (75–100%). The less active micro-catchments were those comprising semi-natural vegetation on T2 and most of T3 micro-catchments, characterized by reforested headwaters and well-maintained terraced tree crops in the valley floors.

The greatest activity was recorded for the event in November 2006, after which the main channel flowed carrying fine and gravel sediments. The April 2006 event produced a medium level response, with almost no flow in the main channel but some in the upper parts. The January 2006 event produced less activity than the events in November and April. The September 2006 event, after a long dry summer, resulted in a minor flow, carrying almost no sediment in the tributaries and some redistribution of fine sediment in the main channel. The April 2005 event was not mapped at this site. Correlation analysis shows, as in S1, that number and length of flow and sediment connected pathway links are significantly related, and that both are related to total rainfall (Table IV).

Mapped Connectivity Patterns in Micro-catchments Draining to a Main Channel: Site 3

S3 site (Figure 6) comprises a main channel (right bank tributary of Cárcavo creek) and several micro-catchments that flow into it. Some micro-catchments present semi-natural shrub-type vegetation, whereas others have either dense reforestation in the headwaters, or olive and almond tree crops. Several check dams restrict sediment movement along the main channel. In the lower section, there is a contrast between the left and right slopes, with left north-facing reforested areas and the right south-facing slopes on semi-natural vegetation. Major vehicle tracks cross south-facing slopes.

As was shown for S1 and S2 sites, the greatest activity was recorded for the November 2006 event (Figure 6), in which the main channel flowed carrying both fine and gravel sediments. Main active pathways were located in the south-facing micro-catchments and bank gullies on the right bank. The upper micro-catchments crossed by the track were most active overall. Degree of vegetation cover in the bottom of rills and gullies differs markedly with aspect, and north-facing, highly vegetated pathways showed little flow or sediment movement at any time.

Table IV. Pearson correlation coefficients for a pairwise comparison of rainfall and connectivity characteristics in S2 site (dark grey and bold, $p < 0\cdot05$; light grey, $p < 0\cdot10$)

	Varia bles	Morphometry									External factor		
		Length of connected pathways			Number of connected pathways			Average pathway length			Rainfall		
Variables		Flow only	Flow and sediment	Total	Flow only	Flow and sediment	Total	Flow only	Flow and sediment	Total	Rainfall (mm)	Max rainfall (60 min)	Rainfall (30 days)
Length of connected pathways	Flow only	**1·00**	0·39	0·80	0·93	0·53	0·80	0·15	−0·41	−0·81	0·31	0·62	0·43
	Flow and sediment		**1·00**	0·87	0·68	0·99	0·86	-0·69	0·55	−0·60	0·98	0·63	0·98
	Total			**1·00**	0·95	0·93	1·00	−0·37	0·14	−0·83	0·81	0·75	0·87
Number of connected pathways	Flow only				**1·00**	0·78	0·96	−0·22	−0·05	−0·93	0·63	0·82	0·67
	Flow and sediment					**1·00**	0·93	−0·59	0·43	−0·67	0·95	0·66	0·98
	Total						**1·00**	−0·41	0·17	−0·87	0·82	0·80	0·85
Average pathway length	Flow only							**1·00**	−0·96	0·41	−0·81	−0·62	−0·53
	Flow and sediment								**1·00**	−0·14	0·68	0·39	0·41
	Total									**1·00**	−0·62	−0·96	−0·52

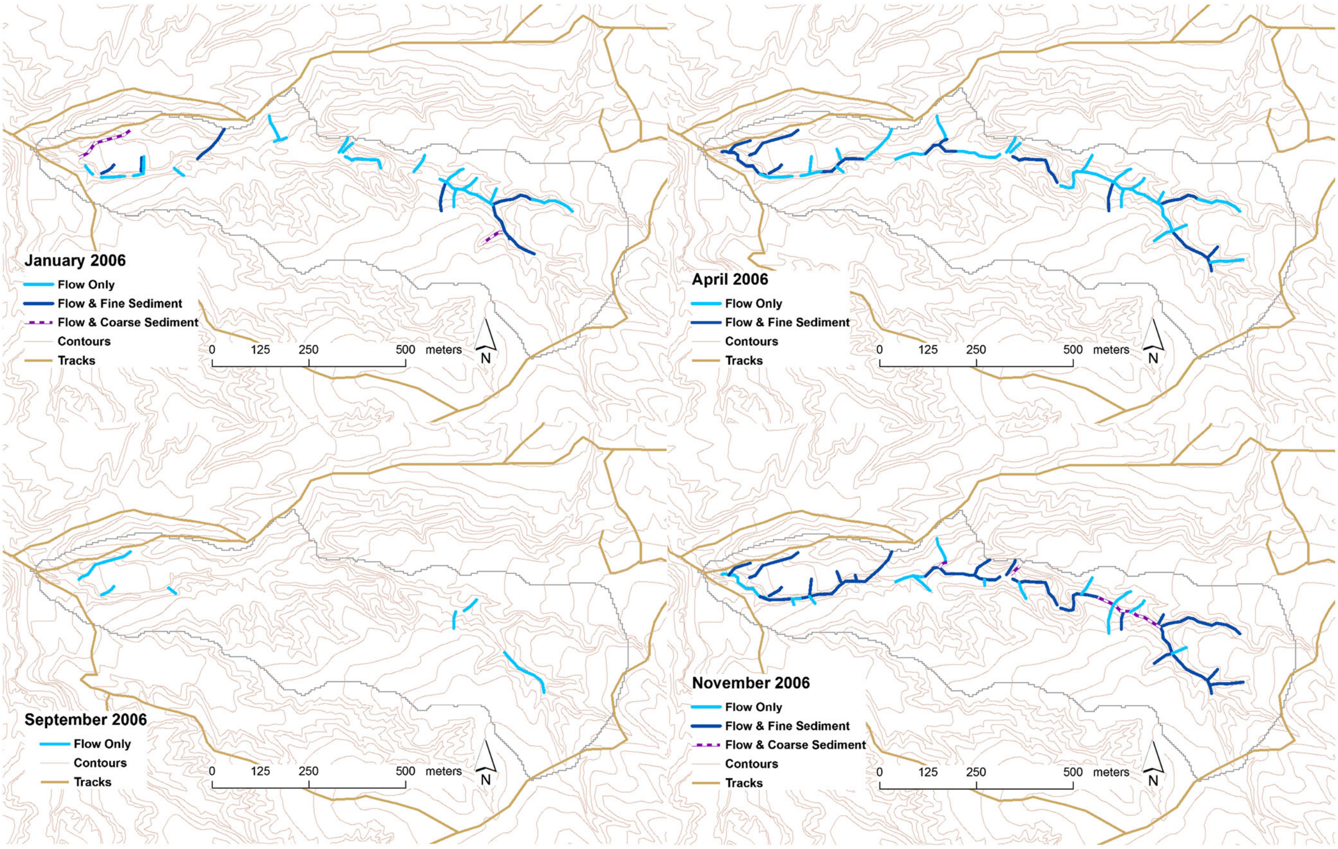

Figure 6. Connectivity patterns in Site 3 (S3) site after monitored events. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

DISCUSSION

Connectivity Mapping and Hotspots

The proposed methodology allowed the identification of real connectivity features during the study period. Repeated after-event mapping revealed most frequent sources, pathways and sinks, distinguishing water and sediment connectivity. This methodology allows characterizing landscape responses in semi-arid climates, typically with highly heterogeneous hydrological and erosion responses (Boix-Fayos *et al.,* 2006). When cross-scale interactions and non-linear processes control system evolution (Cantón *et al.,* 2011), this methodology can be used to identify, map and monitor hotspots in runoff and sediment production from sub-catchment to hillslope scale. This approach has been recommended by Hooke *et al.* (2007) and Hooke & Sandercock (2012) with the aim of increasing the efficiency of revegetation strategies to mitigate erosion and restore degraded lands.

Flow hotspots at hillslope scale were mostly bare and/or crust areas on stony steep slopes, generating quick runoff that triggered erosion immediately downstream in the pathway link. Main sediment source areas at the micro-catchment scale were (i) steep abandoned terraced croplands (Lesschen *et al.,* 2009; Meerkerk *et al.,* 2009), (ii) untended terraced reforestations (Williams *et al.,* 1995) and (iii) headwater areas affected by tracks (Croke *et al.,* 2005). Steeper sections along these pathways over loose soils tend to generate deep rilling and gullying, including on terrace ramps, and constitute major hotspots. Source, transport and sedimentation areas can be delineated and prioritized for designing effective restoration plans. It was also seen that the more vegetated pathways experienced little flow or sediment movement in these events, reinforcing the efficacy of the strategic spatial planning of mitigation and restoration activities using vegetation (Hooke & Sandercock, 2012).

Minor variations in topography and morphology can have a profound influence on pathways, for example, small breaches, ephemeral gullies (Vandekerckhove *et al.,* 1998), low points on tracks or embankments, sinks in the form of terraces or vegetated patches (Lesschen *et al.,* 2009) and fans on footslopes (Faulkner *et al.,* 2008). These features are not easily detected in general surveys or easily measured from secondary sources (e.g. topography, remote sensing images and digital elevation models) but can be observed on the ground. For these reasons, detailed and standardized field surveys are required for an accurate assessment of connectivity and identification of hotspots for restoration. However, the relations are not easily amenable to statistical analysis. Field surveys cannot be replaced by models, as most of them are spatially lumped (Haregeweyn *et al.,* 2013), overestimate overland flow pathways (Poeppl *et al.,* 2012), and target processes are often non-linear and scale dependent (Lesschen *et al.,* 2009).

Connectivity, Landscape and Rainfall Events

Several key characteristics emerge from analysis of the observed patterns. The event in November 2006 was moderately high but was preceded by high antecedent precipitation (over 100 mm) in the previous days. Under these conditions, a threshold was surpassed, and major connectivity response was observed, characterized mainly by a peak in total length of pathways. Events of approximately same size and intensity, as in April 2006 and September 2006 (20 mm), can cause different connectivity responses as reported by Ziadat & Taimeh (2013). Response in April was characterized by a high number of relatively short pathways, whereas in September, longer but fewer flow-only pathways were observed, probably owing to differences in antecedent rainfall. S2 case study revealed an association between total rainfall and length and number of fully connected pathways. Okin *et al.* (2009) considered that increases in length of connected pathways are essential in the initiation and development of desertification processes.

The monitoring period coincided with a drought and below-average annual rainfalls in 2005 and 2006. A longer record with more events is needed for deriving more robust statistical relationships. Events with daily rainfall of <20 mm (such as April 2006) occur several times a year on average, events of 20–30 mm occur two to three times a year, and the event in November 2006 had a calculated recurrence interval of 8 years, based on 35 years' series of nearby stations Almanedes, Calasparra and Cieza. This was the only event that clearly surpassed a threshold and, after high antecedent precipitation (122 mm in 7 days), triggered a major connectivity response.

As Fryirs *et al.* (2007) remarked, connectivity response is controlled by various switches at different scales, resulting in a 'jerky conveyor belt sediment cascade'. Intra-event rainfall characteristics (Cammeraat, 2004) together with antecedent rainfall and soil moisture (Cerdà, 1999; Gómez-Plaza *et al.,* 2001) are well known to cause differences in runoff response, affecting fine-scale hydrological connectivity (Bracken & Croke, 2007). These factors joined with shifting land configuration, owing to agricultural management, resulted in high inter-event variability in connectivity patterns.

Factors Influencing Connectivity Response

Spatial differentiation of response was also evident from measurements and observations with some differences between landscape settings. Field configuration and ploughing restrict connectivity, as deliberately designed. However, in the largest event, some of the embankments were overflowed and broken, so that flow lines tended to follow the main natural drainage pattern. Sources that responded more frequently were located in the upper parts of the sites and characterized by low cover vegetation, soil crusts, shallow and stony soils or areas affected by tracks. Agricultural tracks concentrate runoff, allowing the development of permanent rills, feeding the developing piping system in the lower section of the S1 subcatchment. Tracks and roads promote runoff concentration and gully initiation as stated by Croke *et al.* (2005) and confirmed for the studied area by Lesschen *et al.* (2009) and Meerkerk *et al.* (2009).

Field evidence indicates that some factors at a more detailed scale may have a controlling influence on connectivity patterns: vegetation patterns, micro-topography, soil condition, surface crusting, position of tracks and so forth. More intensive mapping of pathways and hotspot areas in semi-arid landscapes is recommended at a more detailed scale, as spatial averaging of slope and aspect values cannot explain the variability of connectivity responses. It may be the pathway characteristics rather than just micro-catchments characteristics, which are of importance. This has implications for conventional analyses that typically relate sediment yields to broader catchment characteristics.

CONCLUSIONS

Repeat mapping of connectivity after rainfall events allows identification and mapping of sources, links and sinks and their frequencies and thresholds of response. A methodology has been developed and applied in a series of small catchments in SE Spain. Integration of field mapping in a GIS database permits the consistent comparison of flow and sediment connectivity patterns for different events. Factors influencing connectivity patterns can also be interpreted through field assessment and repeat mapping.

Main sources of flow were identified as hardened/crusted areas, bare patches, steep terraced reforested headwaters, low cover south-facing slopes and areas affected by roads and tracks. Antecedent rainfall was important for achieving greater overall connectivity, particularly longer connected pathways connecting the landscape with main channels. Repeated mapping allows the establishment of thresholds of activity at different scales.

This methodology is useful for identifying hotspots in the landscape where erosion and sedimentation are most likely to occur and flow and sediment connectivity pathways are more frequent. These are the areas where establishment of vegetation should be encouraged. The findings of this research were used in the production of practical guidelines for mitigation and restoration of desertified lands (Hooke & Sandercock, 2012).

Further studies should integrate this methodology with detailed micro-topographic and vegetation factors mapping because major catchment characteristics alone do not explain connectivity patterns and localization of pathways. Direct mapping as developed here allows identification of actual pathways, sources and sinks. These can be compared with those predicted by catchment characteristics and models to analyse the influence of the detailed-scale features and landscape configuration on hydrological and erosion responses.

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