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DOI
10.1007/978-3-319-44451-2_2

Publication date
2017

Document Version
Final published version

Published in
Combating Desertification and Land Degradation

Citation for published version (APA):
Hooke, J., Sandercock, P., Cammeraat, L. H., Lesschen, J. P., Borselli, L., Torri, D., Meerkerk, A., van Wesemael, B., Marchamalo, M., Barbera, G., Boix-Fayos, C., Castillo, V., & Navarro-Cano, J. A. (2017). Mechanisms of Degradation and Identification of Connectivity and Erosion Hotspots. In J. Hooke, & P. Sandercock (Eds.), *Combating Desertification and Land Degradation: Spatial Stragegies Using Vegetation* (pp. 13-37). (SpringerBriefs in Environmental Science). Springer. https://doi.org/10.1007/978-3-319-44451-2_2

Chapter 2
Mechanisms of Degradation and Identification of Connectivity and Erosion Hotspots

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Abstract The context of processes and characteristics of soil erosion and land degradation in Mediterranean lands is outlined. The concept of connectivity is explained. The remainder of the chapter demonstrates development of methods of mapping, analysis and modelling of connectivity to produce a spatial framework for development of strategies of use of vegetation to reduce soil erosion and land degradation. The approach is applied in a range of typical land use types and at a hierarchy of scale from land unit to catchment. Patterns of connectivity and factors influencing the location and intensity of processes are identified, including the influence of topography, structures such as agricultural terraces and check dams, and past land uses. Functioning of connectivity pathways in various rainstorms is assessed. Modes of terrace construction and extent of maintenance, as well as presence of tracks and steep gradients are found to be of importance. A method of connectivity modelling that incorporates effects of structure and vegetation was developed and has been widely applied subsequently.

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J. Hooke, P. Sandercock, *Combating Desertification and Land Degradation*,
SpringerBriefs in Environmental Science, DOI 10.1007/978-3-319-44451-2_2

Keywords Soil erosion processes • Runoff connectivity • Sediment connectivity • Erosion hotspots • Agricultural terraces • Connectivity mapping • Connectivity modelling

2.1 Soil Erosion and Degradation in Desertified Mediterranean Lands

The Mediterranean environment is affected by desertification. Desertification means land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities (UNCCD 1994). Of all the processes leading to desertification, soil erosion is considered to be the most important degradation process in Mediterranean Europe (Poesen et al. 2003). Erosion and degradation occur across a range of scales and land units in the Mediterranean landscape. Within each of these scales and land units it is possible to identify particular processes of erosion and land use practices which have directly or indirectly contributed to desertification in the region.

Erosion is particularly important in agro-ecosystems of marginal hilly areas characterized by high water deficit and high inter-annual variability in rainfall. The change in land use from a semi-natural vegetation or traditional terraced orchards to intensified plantations with an extremely low crop cover, leaving most of the soil exposed, has large impacts on hydrology and land degradation (Beaufoy 2002; De Graaff and Eppink 1999), with both on-site effects such as gullying and off-site effects such as flooding and reservoir sedimentation.

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In semi-natural and abandoned lands, disturbances to the spatial heterogeneity of vegetation cover result in concentrated flow (Cammeraat and Imeson 1999; Tongway and Ludwig 1996) leading to high degradation rates and soil quality loss. Many abandoned lands are also terraced by earth dams and with the halt of cultivation, the maintenance of terraces is also stopped. This leads to the deterioration of the terraces, an increase in the length of slopes over which runoff occurs and accelerated rates of erosion. Soil retained above these terraces may be eroded and released under extreme runoff events (Cammeraat 2002).

Reforestation using trees has been widely applied throughout the Mediterranean; however, due to the harshness of semi-arid environments their success has been severely limited (Zhang et al. 2002). Extensive terracing of lands was undertaken across the Mediterranean in the 1960s and 1970s using heavy machinery, a practice considered to improve water yield to the plants and accelerate development of vegetation and ecosystem restoration. However, in many cases, land degradation was triggered by these aggressive techniques, increasing soil erosion (Chaparro and Esteve 1995; Williams et al. 1995) and reducing soil quality (Querejeta 1998). Castillo et al. (2001) indicate that the sidebanks produced may also be a source of sediment and gully initiation because of the long-term devegetation and steep gradient.

Gully erosion is a particular problem, responsible for significant on-site soil losses and off-site consequences (Poesen and Valentin 2003). In Mediterranean areas, the evidence from several studies is that gully erosion may be responsible for up to 80 % of total soil losses due to water erosion, whereas this process in many cases only operates on less than 5 % of the land area (Poesen et al. 2003). Once developed, gullies increase the connectivity of flow and sediment transfers from uplands to lowland areas through the drainage system. Reducing gully erosion, will lead to less sediment export, less reservoir sedimentation, lower flood risk and allow more water in uplands to infiltrate. Similarly, deterioration of soil resources and ecosystems is also apparent in valley floors, mainly as a result of erosion during high flows. Efforts that are made to mitigate runoff and concentrated flow leading to gully erosion would also be effective in reducing the potential for erosion and degradation of valley floors.

2.2 Processes

Most of the soil erosion and land degradation in the Mediterranean region occurs by the movement of surface material downslope via water flow transport in rills, gullies and soil pipes. Rainsplash can have an effect on bare soil and lead to crusting, which further decreases infiltration rates and increases runoff. Some erosion may take place in overland flow in unrilled zones at the top of slopes but quickly water flow tends to be concentrated into pathways which then incise at some distance downslope producing rills. Erosion is greatest where flow velocities or shear stresses are highest, combined with low resistance of the soil or surface, i.e. on steep gradient areas, and where runoff generation is greatest, notably bare surfaces. These are erosion hotspots. Erosion is much reduced where the vegetation cover is >30 % (Thornes and Brandt 1993). Amount of runoff increases downslope and thus also length of slope increases liability to erosion. Once gullies or piping develop then these can be propagated rapidly up and downslope. For all these reasons increase of vegetation and particularly emplacing vegetation in the pathways of flow can reduce soil erosion and sediment flux. Infiltration rate of the surface is a major control and once soil erosion begins then soil removal tends to decrease infiltration rate, which increases runoff which in turn increases erosion and so decreases infiltration rate still further. This positive feedback relation can proceed until all soil is removed and more resistant bedrock is reached. Agricultural productivity of such areas becomes rapidly reduced. Thus soil erosion tends to accelerate once initiated.

Ruiz-Navarro et al. (2012) studied the relationship between landscape attributes and soil quality in Cárcavo catchment. Soil quality is clearly structured in a gradient of fertility/quality where soil carbon, nutrient availability, cation exchange capacity, relatively low pH and water holding capacity are strongly associated. Higher quality soils are positively associated to landscape configurations of flow convergence and low solar radiation (low hydric stress) and dense vegetation and negatively associated to areas of intense gully formation on highly erodible lithologies and scarce vegetation (active erosion processes). They also found that the positive correlation to dense vegetation and water favourable conditions is higher at finer resolution (5–10 m) while the negative association to erosion-prone configurations is higher at coarser resolution (20–40 m). This is interesting as the topographic structures favouring flow convergence simultaneously promote vegetation development and erosion processes, and, depending on the connectivity of flows, the balance may go one way (vegetation and higher soil quality) or the other (erosion and poor soil quality), this being consistent with better association of positive scenarios (vegetation predominance) at finer scales (flows have not enough energy to connect) and negative scenarios (erosion dominance) at coarser scales (flows have higher energy and overcome vegetation resistance to connection). The system would act as a tipping point threshold with alternative states of vegetation positive feedback or erosion positive feedback.

2.3 Connectivity Concept and Methods

When the RECONDES project was designed very little work applying the connectivity concept to the Mediterranean environment and to practical uses had been undertaken. Methods of mapping, identification, and quantification were still poorly developed, with a few exceptions e.g. van Dijk et al. (2005) and the work of Cammeraat and Imeson (1999), Cammeraat (2002), Cammeraat (2004) on hillslopes and Hooke (2003) in channels. Since then much development has taken place, particularly in the conceptual ideas, including ideas of structural and functional connectivity (Lexartza-Artza and Wainwright 2009; Okin et al. 2009; Wainwright et al. 2011), and in relation to applications (e.g. Brierley et al. 2006;

Croke et al. 2005; Evrard et al. 2007). Much discussion on runoff and hydrological connectivity has taken place (Bracken et al. 2013). Various methodological developments and methods of mapping arose from the RECONDES project which produced a very rich and varied series of contributions (Borselli et al. 2008; Lesschen et al. 2008a, b, 2009; Marchamalo et al. 2016; Meerkerk et al. 2009; Sandercock and Hooke 2011; Vigiak et al. 2012). Some of those contributions allowed for the identification of bias in data elaboration, due to the utilization of the maximum potentially draining area instead of the actually draining area which is often smaller (Rossi et al. 2015). This allowed for the introduction of a vegetation/land-use effect on the gully-head threshold equation (Torri and Poesen 2014). Rossi et al. (2013), working in another EU-funded project (BIO-SOS), adopted the RECONDES approach, modifying it to deal with data derived by (VH resolution) satellite imageries, and linear artificial structures such as roads, which are major modifiers of water and sediment fluxes. These same concepts were applied for modifying the RUSLE application in catchments, producing a connectivity term which defines the potential sediment contributing area at each position in a catchment (Borselli et al. 2008). The approach was later expanded and applied to mass movement sediment contribution to streams (Borselli et al. 2011) within another EU-funded project (DESIRE).

The aim of the RECONDES project and the research illustrated here was to develop and apply methods of identification of connectivity in the field in order to understand the spatial patterns and dynamics as the basis for development of spatial strategies, and in order to generate data with which to validate models. Because of the lack of methods and examples of actual field mapping of connectivity it was necessary to develop a methods protocol (Cammeraat et al. 2005). Zones and pathways of flow and locations of erosion and sedimentation were mapped from signs of water flows and sediment production/sedimentation that can be visually observed e.g. rills, local deposits, splash pedestals, flow lines delineated simply by alignment of dead leaves. Field mapping of features created in an event required use of a base map with land uses and topographic details. Some mapping prior to events was done to add details of structures etc. and to assess potential (or structural) connectivity. After a rainfall/flow event mapping was undertaken using GPS and photography to mark points. Individual features such as depth of rills and deposits were measured.

To fulfil the objectives, connectivity mapping and assessment needed to be carried out at a variety of scales. This was done mainly at land unit, subcatchment and channel scale but ranged from plot to catchment scale (Fig. 2.1). At each of these hierarchical scales representative areas were selected for detailed mapping and instrumentation. Techniques of mapping needed to vary with scale and type of terrain. The approaches and methods are illustrated in the following sections together with the results on the main patterns, erosion hotspots and pathways. The land units identified are the major ones present in the catchment and typical of upland agricultural areas of the southern Mediterranean region of Europe. These are: afforested land, rainfed croplands and abandoned/semi-natural lands.

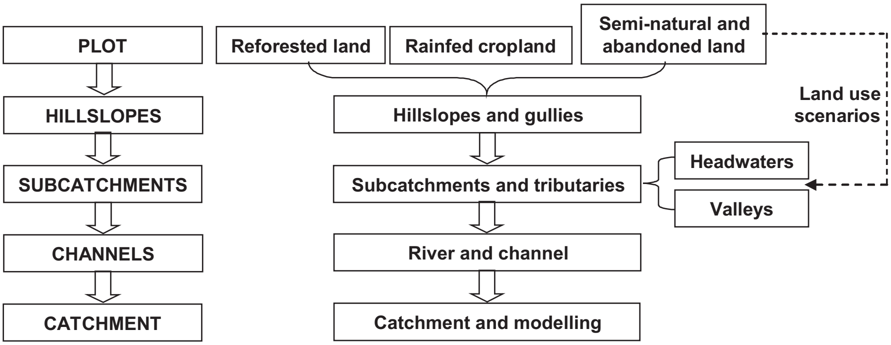

Fig. 2.1 Different scales of analysis of hydrological connectivity and sediment pathways

2.4 Methods and Results at Various Scales

2.4.1 Plot Scale

At the finest scale plot descriptions and maps of vegetation patterns and the relations to the surface, i.e. parent material, crust and erosion features, were made for different runoff response areas (Vijfhuizen 2005). Figure 2.2 gives an example of one of the surveys at the finest scale. This shows the pattern of flows in relation to individual plants and to bare and crusted areas of soil. Mapping and analysis at this scale is relevant if the need is to understand the detailed processes. However, in the overall strategic approach here it is more important to identify the main runoff generating zones or hydrological units and areas vulnerable to erosion and how they are connected downslope.

2.4.2 Land Unit Scale

2.4.2.1 Reforested Land

A field study was conducted to analyze the effects of terracing on the connectivity of a small (1.13 ha) fully reforested catchment (Fig. 2.3). Using field surveys and analysis of orthophoto images with a 0.5 m resolution, five response units were identified. These response units are based on two main criteria: (i) morphology of the unit (slope, type of reforestation/terraces, bedrock, vegetation), and (ii) evolution of erosion and hydrological features. The six units identified were: terraces perpendicular to the main slope, terraces not completely perpendicular to the main slope, steep terraces with long talus, or partially deteriorated, terraces with long natural talus, and sink zones.

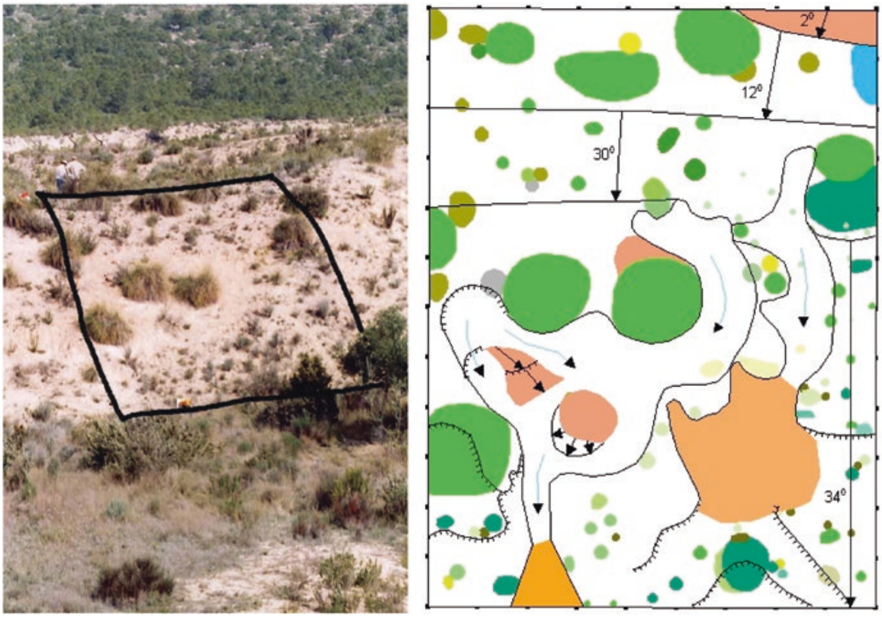

Fig. 2.2 Example of fine scale connectivity mapping. *Left* the actual area and *right* the mapping. *Green dots* indicate different types of vegetation, *arrows* active flow lines of water and lines with hatches small rims, delimiting small terracettes, depressions or channels on the surface (Vijfhuizen 2005)

A map of hydrological connectivity was drawn from the tracks of flow lines by Boix-Fayos, Navarro-Cano and Castillo (Fig. 2.3). It has been made following the guidelines of Cammeraat et al. (2005) (Connectivity and Response Units mapping). The units with less signs of concentrated flow are the *perpendicular terraces* and the *terraces with long natural talus*. The *steep terraces, long talus* unit favours the convergence of flow due to a combination of steep slope and the not complete perpendicularity of the terraces. In other cases, just due to the steep slope, it favours the connection between two terraces breaking the talus through a concentrated flow line. The *terraces not completely perpendicular* unit is the one where more concentrated flow lines appear due to the channelization of water along the main longitudinal slope. In some cases clearly defined long rills and gullies appear parallel to the contour of the terraces, and parallel to the main drainage line of the catchment. Therefore hotspots include defective terraces (not perpendicular to hillslope), localised degraded areas in terraces and semi-collapsed terraces. Steep side banks are also points where erosion and connectivity is favoured.

A total of 40 wooden stakes with water sensitive tape glued on the upslope side were placed all around the catchment in order to test the connectivity map. The stakes were geo-referenced with high-precision GPS. After the storm event on November 2006, water marks on stakes were recorded. From a preliminary analysis of these records, it can be concluded that defective terraces, which are not

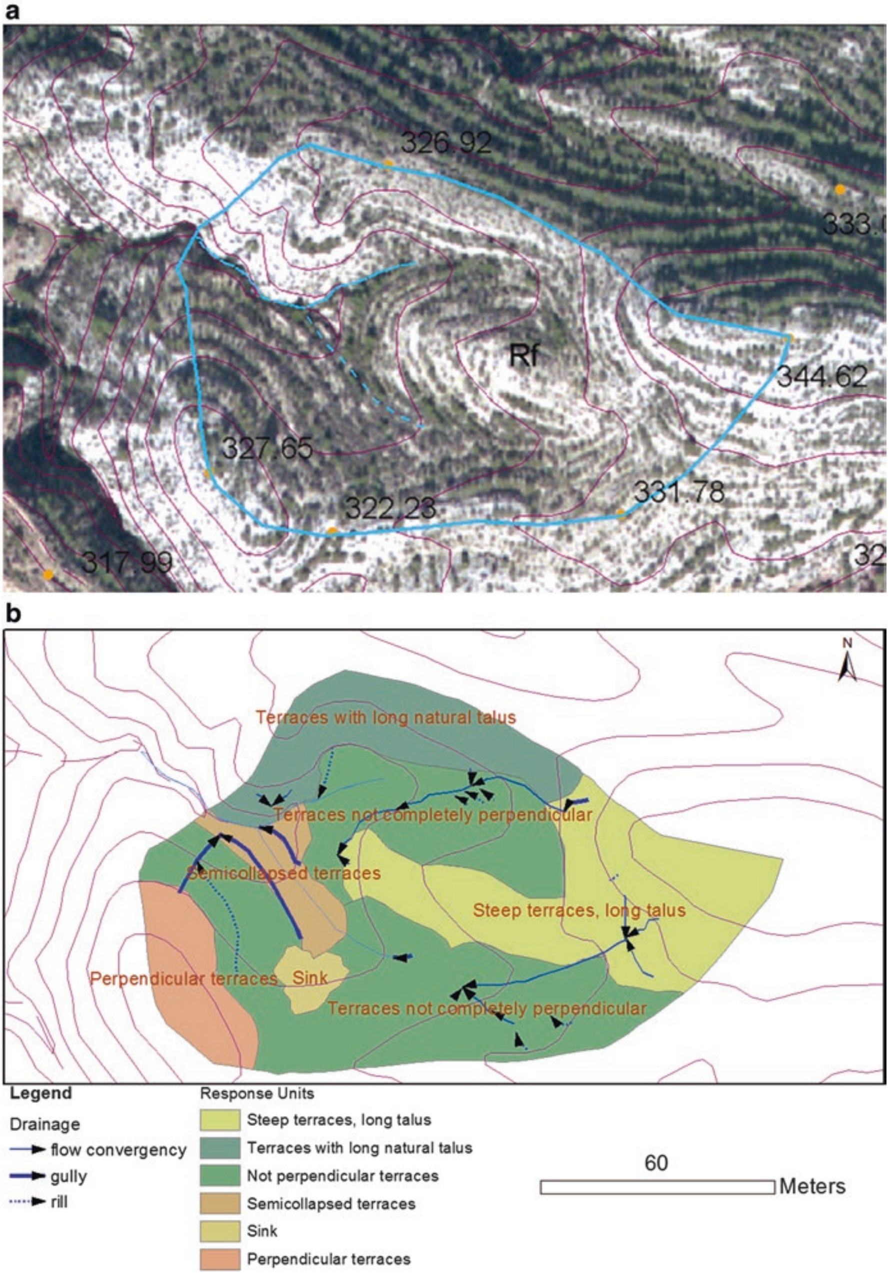

Fig. 2.3 (**a**) Aerial photograph of study area in a reforested sub-catchment (Barranco del Lobo); (**b**) Map of hydrological connectivity in the area: It was identified that reforestation terraces non-perpendicular to the slope increased flow convergence and therefore the initiation of concentrated erosion in the form of rills or gullies (By Boix-Fayos C., Navarro-Cano J. and Castillo, V., in Hooke and Sandercock 2012)

perpendicular to slope, act as fast runoff pathways. Local default in terraces seems to increase the hydrological connectivity. Finally, higher connectivity is favoring the collapse of old reforestation terraces and the migration upstream of the drainage network. This validation confirmed the identified hotspots.

2.4.2.2 Rainfed Cropland

Land degradation by water erosion on rainfed croplands is directly related to the low canopy cover of cropping systems in dry environments. On cereal fields, the application of a fallow year is common, leaving the soil bare throughout the year. In the almond and olive orchards the fields are ploughed several times a year to keep them free of weeds. The aim in this cropland land unit was to assess the feasibility of use of a cover crop to provide a vegetative cover and reduce erosion, particularly under orchard crops. For an effective implementation of cover crops it is necessary to identify the locations in the landscape which promote the connectivity of water and sediment. Such hotspots should have the highest priority in any implementation scheme. Surveys took place after rainfall of different magnitude and intensity in 2006 (Fig. 2.4). The mapping included patterns of concentrated flow and erosion, terrace breaches and pipes.

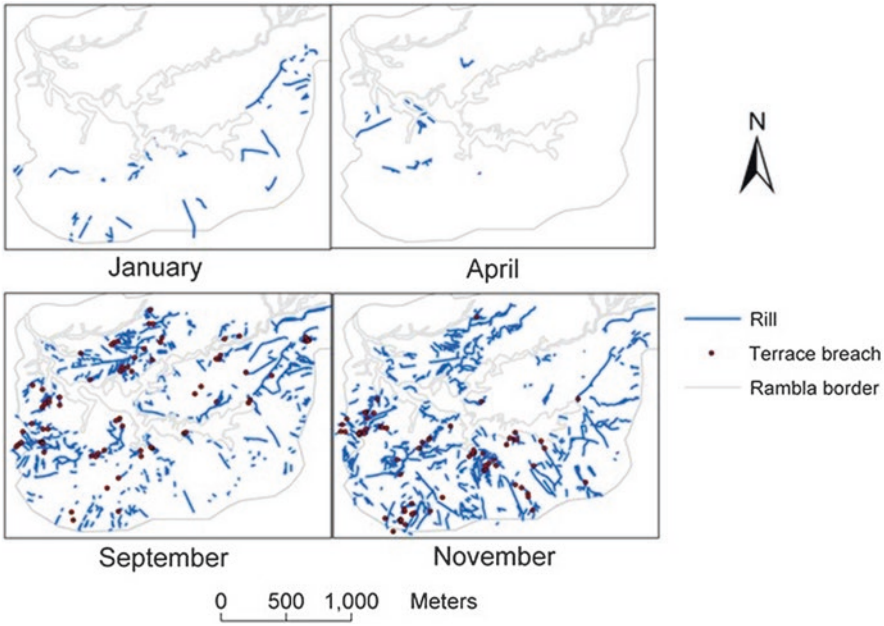

Fig. 2.4 Pathways of concentrated flow in the southern sub-catchment of Cárcavo after rain events in 2006. The mapped terrace breaches include both existing and new breaches (After Meerkerk et al. 2009)

Patterns of runoff, evidence of flow lines and signs of erosion were mapped in the four main rainfall events (Fig. 2.4). Some general observations were made during the field surveys (Meerkerk et al. 2009):

1. There are no runoff/erosion problems on well-maintained terraces with contour tillage. However, on terraces that are longer in the slope direction (e.g. > 20 m) and have a more than gentle slope (e.g. >2°), runoff/erosion is common.
2. The weak parts of the (well maintained) terraces are the access tracks that pass at the sides. Most of these tracks are at the sides or in the middle of the terrace. Sometimes, the tracks continue straight down the hill, passing a large number of terraces. In this configuration, the track forms a channel of concentrated flow. The compacted surface has a low infiltration capacity and will produce runoff for rains as small as 8 mm. Sedimentation occurs in places where the slope is more gentle, at the lower end of the road, and sideways onto the terraces.
3. The shape of the terrace surface is quite important. If a terrace surface has a thalweg, then the probability of concentrated flow increases considerably. An effective/ideal terrace has a straight, horizontal surface perpendicular to the slope.
4. Dirt roads have the highest runoff coefficient of all surfaces and it is here that the first runoff is produced during an event. See for example the connectivity map of January in Fig. 2.4, where runoff is concentrated on road segments. Motha et al. (2004), in a catchment of comparable size in Australia, showed that the road surface may contribute 40–50 % of the sediment at the catchment outlet, despite the fact that it covers only 1 % of the catchment.
5. On agricultural fields erosion/deposition features are masked during most of the year because of the practice of frequent tillage in the orchards and vineyards. They are only visible between the rain event and the next tillage pass.
6. Just a small part of the sediment that was transported by overland flow following the large rain event of November reached the main stream channel (rambla). In the agricultural area, most of the sediment was deposited on terraces or other relatively flat locations.

Summarising the observations above, three important hotspots of runoff and erosion can be distinguished in rainfed croplands: road surfaces, thalwegs and valley bottoms within the fields, and terrace access tracks.

The role of field borders was also examined. An assessment was made of the occurrence and condition of the terraces and retention banks in Cárcavo in 1956 (aerial photos) and in 2005 (fieldwork). Between these dates, the number of terraces decreased by 36 % and the number of retention banks by 28 %. Of the terraces 54 % were intact in 2005 as well as 50 % of the retention banks (Bellin 2006). The remaining part was classified as "permeable", defined as terraces/banks having one or multiple breaches; lacking an intact rim of + 30 cm height; or lacking a counter slope near the terrace edge.

During the 1956–2005 period, the average upslope drainage area of the terrace banks increased from 0.24 to 0.64 ha. These results indicate a clear increase for the potential connectivity within the landscape. The decline in soil conservation

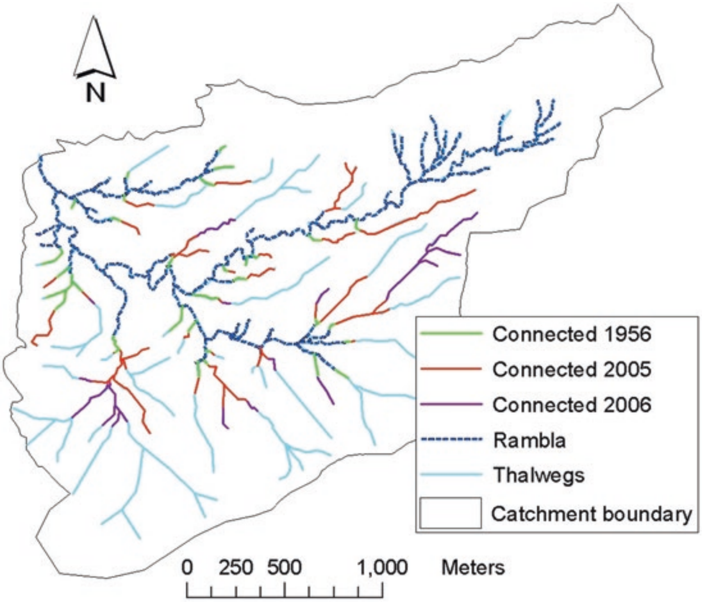

Fig. 2.5 The effect of the decline of conservation structures on the length of the thalwegs that are directly connected to the rambla (After Bellin et al. 2009)

structures is reflected in larger fields and a lower capacity to counteract concentrated flow towards the ramblas (main channels). The observed changes are probably related to the mechanisation of agriculture after 1956. The effect of the decrease of terraces and dams on the connectivity of thalwegs towards the rambla is illustrated in Fig. 2.5.

2.4.2.3 Abandoned Land and Semi-Natural Areas

Similarly, connectivity was mapped in areas that had formerly been used for agriculture. A gully and terrace failure survey was undertaken. In June 2005 abandoned sites and similar cultivated sites were surveyed for gullies to test the hypothesis that abandoned land is more vulnerable to gully erosion than cultivated land. Six field sites were selected, three sets of paired abandoned and cultivated sites, with same lithology and topographic position. The following characteristics were included: gully activity (three classes), vegetation cover in the gully (three classes), type of gully head, slope, and size of the gully. Table 2.1 shows the results of this gully survey. All abandoned sites had more gullies and a higher gully density than the comparable cultivated sites. On one of the cultivated sites no gully at all was found. Also, the estimated volume of each gully was larger on abandoned sites. Gully activity was higher for most abandoned sites, while vegetation cover in the gully was not significantly different (Lesschen et al. 2007).

Table 2.1 Mean characteristics of gullies for each site

Site	Land use	Position	Gullies	Density	Activity[a]	Vegetation[a]	Volume
			Number	Gully/ha			m^3
1	Abandoned	Plateau	18	1.1	1.7	1.0	12.4
2	Almond	Plateau	5	0.5	0.6	1.2	4.0
3	Abandoned	Channel head	18	12.6	1.8	0.9	10.1
4	Almond	Channel head	7	2.1	1.9	0.7	3.0
5	Abandoned	Valley	11	2.5	1.6	0.8	0.8
6	Almond	Valley	0	0	–	–	–

[a] Activity and vegetation are ranging from low (1) to high (3)

More intensive analysis of the processes and their effects was undertaken in the instrumented upper part of the catchment under abandoned land. The aim was to study the development of vegetation patterns after abandonment and how these patterns affected soil moisture, soil physical properties at the fine scale and how this affected hydrological connectivity (Lesschen et al. 2008a). From aerial photographs and field surveys 58 abandoned fields were identified in the Cárcavo basin. These fields were surveyed and the following properties were described: previous land use, parent material, vegetation, age of abandonment, erosion features, and presence of terraces or earth dams. Using ArcGIS the field boundaries were digitised and by overlaying the map with a DTM the following properties were determined as well: surface, altitude, slope, drainage area and solar radiation. The 58 fields were then classified into abandoned fields with erosion and without erosion. To be classified as abandoned fields with erosion, the field should show signs of at least moderate erosion, being visible as gully, terrace failure or well developed rill. These two groups were compared using the Pearson's chi-square test for binary variables and the *t*-test for continuous variables. For the detailed analysis of sediment delivery rates we selected an abandoned field, which was located in a valley bottom just before a channel incision.

From the 58 abandoned fields 32 were classified as fields with moderate to severe erosion. Table 2.2 summarizes the average properties for abandoned fields with and without erosion and indicates if differences between the two groups are significant based on the Pearson's chi-square and the *t*-test. The significant ($p<0.05$) differences between the two groups, based on sufficient observations, are cereals as previous land use, presence of terraces, and maximum slope (Lesschen et al. 2008b). That steeper slopes increase the occurrence of erosion is obvious, but the presence of terraces as a risk factor for erosion seems surprising. The presence of terraces implies that the field is located on sloping land and in addition the terrace topography marks steep gradients on the terrace walls, which makes them vulnerable to gully erosion and piping, especially after abandonment. The last significant factor was cereals as previous land use. An explanation might be the negative land management of cereal cultivation with high soil losses (Lasanta et al. 2000), which

Table 2.2 Averaged properties for abandoned fields with and without erosion

Properties	No erosion	Erosion	Significance[a]
Number of fields	26	32	
Previous land use (number of fields)			
Cereals	8	19	**0.030**
Almonds	14	13	0.315
Grapes	4	0	*0.021*
Parent material (number of fields)			
Marl	11	16	0.559
Colluvium	6	13	0.157
Keuper	4	2	*0.256*
Sandstone	3	1	*0.209*
Limestone	2	0	*0.110*
Vegetation (number of fields)			
Mainly herbs	12	12	0.506
Mixed herbs, grasses and shrubs	9	18	0.100
Mainly shrubs	5	2	*0.131*
Field properties			
Surface (ha)	2.6	2.0	0.450
Age of abandonment (year)	9.9	9.2	0.712
Fields with terraces	7	21	**0.003**
Fields with earth dams	7	10	0.719
Mean altitude (m)	389	373	0.230
Maximum slope (degrees)	13.8	18.1	**0.016**
Mean slope (degrees)	5.1	5.7	0.288
Maximum drainage area (ha)	15.3	13.5	0.829
Mean solar radiation (MJ cm^{-2} year^{-1})	0.82	0.81	0.769

[a] Variables with values in italic had too few observations to be reliably significant

degraded the soil already before abandonment. Figure 2.6 shows the setting of the field site and the calculated sediment losses after subtracting the current DTM with the terrace failures from the 1984 DTM. The main terrace failures are clearly visible with incisions of more than one metre, nevertheless some sedimentation has also occurred, especially below the terrace walls. The average surface lowering since abandonment was 13.8 cm, resulting in a net erosion rate of 87 t ha^{-1} year^{-1}.

This rate is higher than the average 12 t ha^{-1} year^{-1} calculated from severe gully erosion studies (Poesen et al. 2003) and much higher than the usual range of 0.1–1 t ha^{-1} year^{-1} under semi-natural vegetation (Martínez-Fernández and Esteve 2005b). Abandonment of agricultural land is widespread and increasing in Spain and can potentially lead to a considerable increase in erosion in semi-arid areas. Abandoned terrace fields are especially vulnerable because of gully erosion through the terrace walls. In the Cárcavo basin more than half of the abandoned fields have moderate to severe erosion and the calculated sediment delivery rates are high.

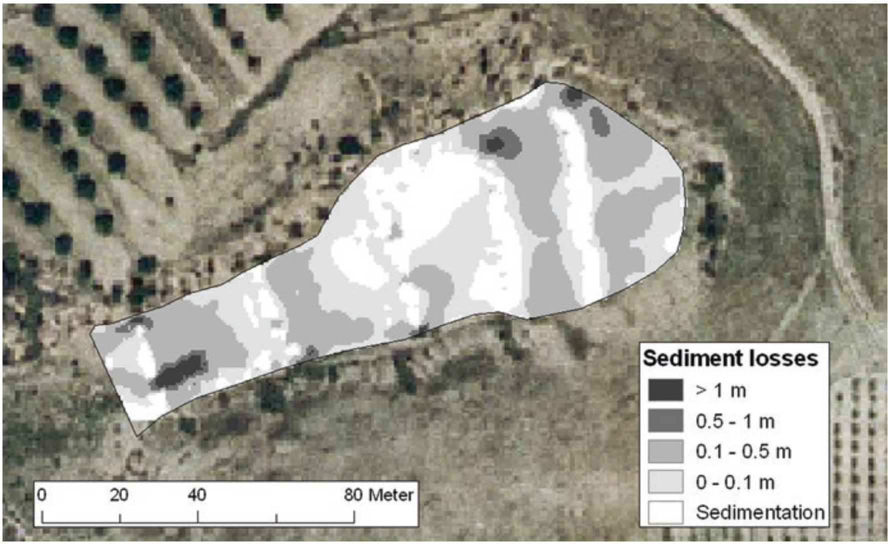

Fig. 2.6 Sediment losses for the terrace field since abandonment in 1984

2.4.3 *Sub-Catchment Scale*

Despite increasing research on connectivity at plot and land unit/hillslope scales, more 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. An experiment was set up to characterize and assess connectivity for events at the subcatchment scale (0.1–1 km^2) under different land use scenarios. This experiment links the research done at land unit/hillslope scale and river channel scale, filling the gap of knowledge between them.

The objectives of this research were to: 1. map the actual pathways of flow and sediment under different land use scenarios for a range of rainfall events; 2. quantify the frequency of response for the identified pathways; 3. estimate rainfall thresholds at this scale; and 4. evaluate the relative weight of relevant factors (land use patterns, topography, geology, roads and tracks, agricultural practices) in influencing connectivity and the delivery of sediment. This analysis also aimed to identify erosion hotspots at the subcatchment scale.

A set of three sub-catchments between 10 and 49 ha in size were chosen within the Cárcavo catchment for detailed connectivity mapping (UOP subcatchments) (Table 2.3).

Table 2.3 Characterization of the studied subcatchments

Id_Exp	Geology	Land use in headwaters	Land use in valley floor	Area (ha)
UoP1	Marls	Abandoned crops	Almond & Olive Trees	14
UoP2_T1	Marls	Reforestation	Reforestation	10
UoP2_T2	Marls	Reforestation	Reforestation	21
UoP2_T3	Marls	Reforestation	Almond & Olive Trees	23
UoP3 (lower)	Marls	Reforestation	Almond & Olive Trees	49

Figure 2.7 shows the results of the mapping and analysis of sources, linkages and sinks (geomorphological map), frequencies of response and rainfall thresholds in the sub-catchment UOP1. The following results emerge:

1. Field configuration (mainly terraces and embankments) restrict flow and sediment movement across the landscape. However, in the largest event some of the embankments were overflowed and broken, so that flow lines tended to follow the main drainage pattern.
2. A great percentage of identified linkages are constant pathways that respond after most rainfall events in spite of constant human labouring and levelling activities.
3. Events of approximately the same size (20 mm) and intensity, as the ones in April 2006 and September 2006, cause different connectivity responses. This may be due to differences in rainfall prior to events.
4. An event occurring after a series of rains, as in November 2006, may cause intense activity in terms of erosion and sedimentation.
5. Sources that responded more frequently were located in the upper part of the subcatchment and characterized by low cover, semi-natural vegetation over shallow and stony soils.
6. The agricultural track concentrated runoff allowing the development of an almost permanent rill that fed the head of the developing piping system in the lower section of the subcatchment.
7. Some rills and features required at least 30 mm of rainfall preceded by over 100 mm in 3 days to show activity. These rills were located mainly in the lower agricultural part of the subcatchment and are frequently ploughed (4–5 times every year).

Analysis of frequency for the recorded activity at UoP3 showed that the most active links (75–100 % frequency) came from southern faced micro-catchments affected by tracks or reforested headwaters. Less active links (0–25 %) were those in the northern-faced vegetated slopes, often having vegetated channels.

The main conclusions of the work exemplified for small catchments are summarised below:

- Repeated mapping of connectivity after rainfall events has been effective in identifying the flow and sediment sources, links and sinks and the frequencies and thresholds of response.

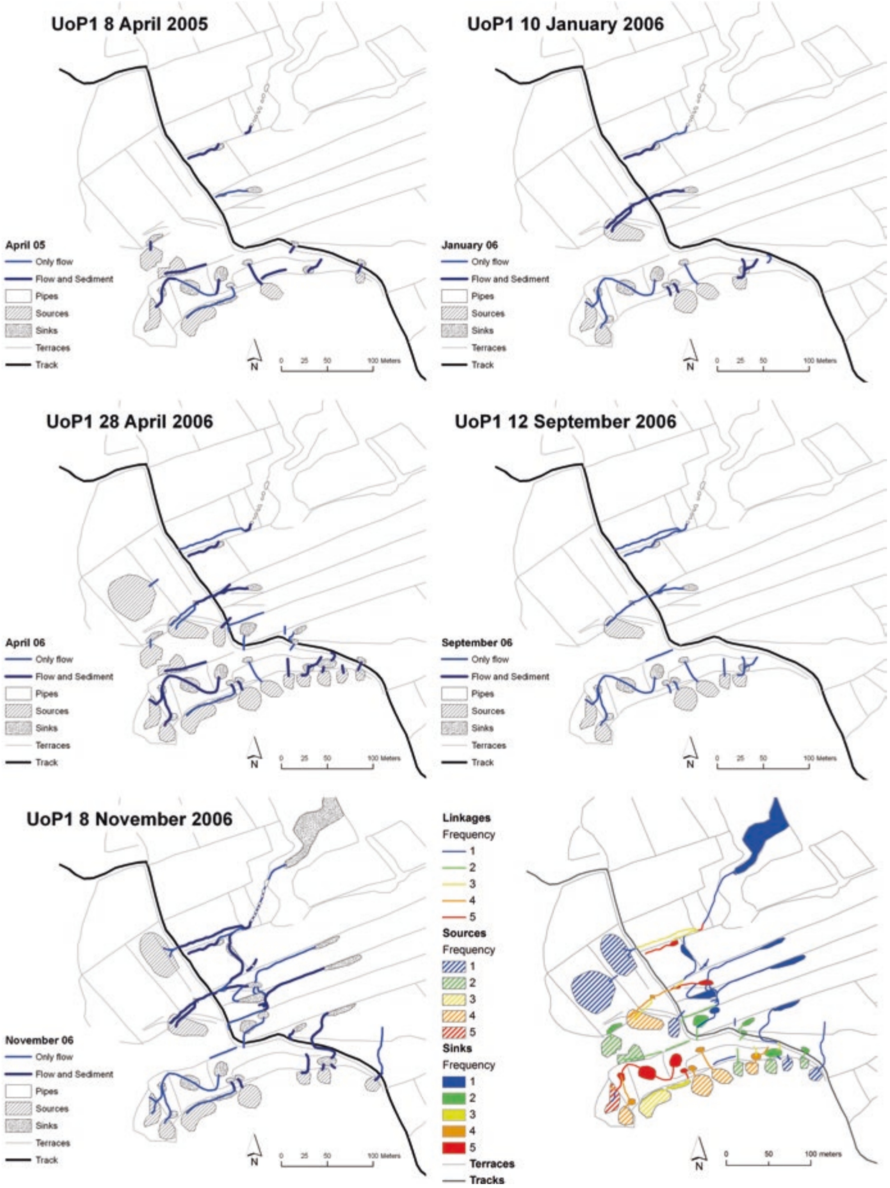

Fig. 2.7 Repeated connectivity assessment in UOP1 (After Marchamalo et al. 2016)

- Connectivity pathways differ in their type of (flow vs. flow & sediment linkages) and in their frequency of response (constant vs. ephemeral). We can distinguish established vs. ephemeral pathways, some of them being event-created pathways and others human-induced pathways (drainage lines, tractor passes).

- Main sources of flow and sediment were identified: these are hardened areas, bare patches, reforested headwaters, low cover south faced slopes and areas affected by roads and tracks. Less active areas were characterized by semi-natural vegetation or the combination of reforestation and semi-natural vegetation in the headwaters and crops in the valley floors.
- Antecedent rainfall was important in inducing greater amounts of runoff and erosion in a 30 mm event in November 2006 than recorded for previous events. This response was characterized by the formation of new rills over the ploughed fields and the activation of previously inactive linkages, which resulted in high overall connectivity for the subcatchments and the whole Cárcavo catchment. During this event the main channel flowed from the headwaters to the lower parts. This formed the basis for establishing thresholds between linkages that reacted for smaller events, those that reacted for November 2006 and those that never reacted during the monitoring period.
- This methodology is useful for identifying hotspots in the landscape where erosion and sedimentation is most likely to occur and connectivity pathways are more frequent. These then form the areas where establishment of vegetation should be encouraged.

Using the evidence from the rainfed cropland areas and the abandoned land the functionality of terraces and vegetation barriers in accumulating water and sediment was further assessed in a sub-catchment approach, combining the flow connectivity observations of Meerkerk et al. (2009) in a catchment with mixed land use, of approx.10 km^2 which forms one of the tributaries of the Carcavo basin. Cumulative runoff, erosion and sedimentation were studied, comparing the current situation with presence or absence of vegetation patterns and terraces. The model shows that the spatial arrangement of sources and sinks at the fine to broader scale (e.g. vegetation patterns or terraces) dictate much of the hydrological (dis)connectivity at the catchment scale (Figs. 2.8 and 2.9) (Lesschen et al. 2009). Rates of sedimentation, erosion and sediment yield at the catchment scale were also calculated and showed that the vegetation and terraces are highly effective in reducing the sediment yield at the broader scale and increasing sedimentation at the local scale (see Table 2.4).

2.4.4 Channels

Processes of degradation along river channels are typically associated with floods. The geomorphic effectiveness of a flood may vary in response to a range of factors including the magnitude, frequency and ordering of previous events and the cumulative effect they have on the channel form (Hooke 2015; Poesen and Hooke 1999; Wolman and Gerson 1978). Thresholds for degradation will vary in association with changes in channel morphology, vegetation type and the calibre of sediments comprising the bed and banks.

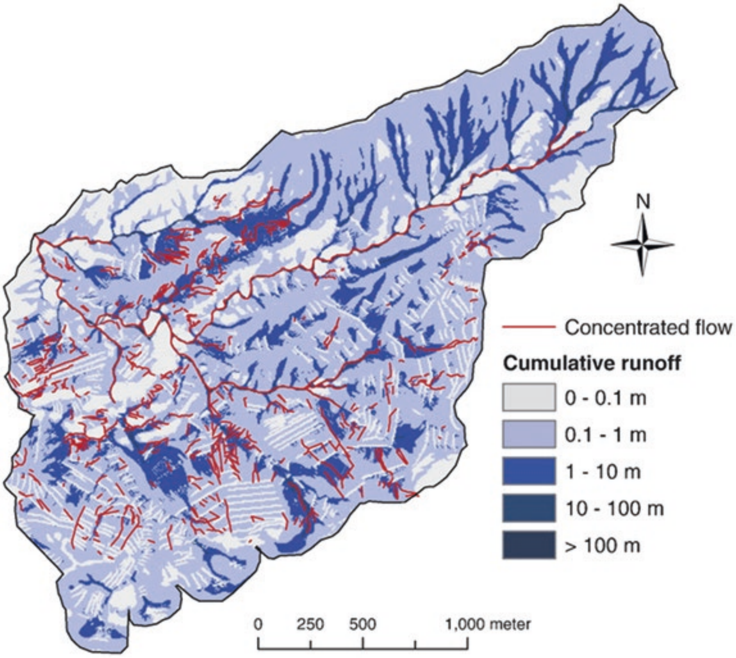

Fig. 2.8 Cumulative runoff concentration (*shades of blue*) and observed runoff (*red lines*) (From Lesschen et al. 2009)

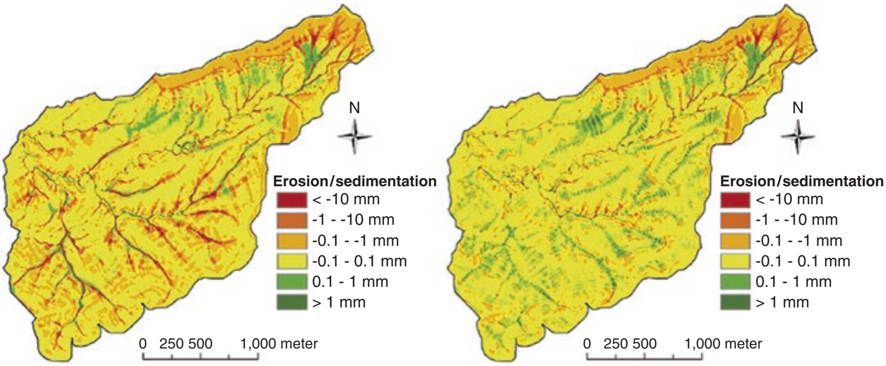

Fig. 2.9 Erosion and sedimentation without terraces (*left*) and with all terraces (*right*) functioning (From Lesschen et al. 2009)

Table 2.4 Model output showing the effect of vegetation and terraces on the erosion and sedimentation (Data after Lesschen et al. 2009)

		Scenario			
Processes		Current	No vegetation	No terraces	All terraces restored
Erosion	Ton ha^{-1}	38.1	56.4	84.8	32.0
Runoff percentage	%	6.8	9.8	25.9	5.2
Sedimentation	Ton ha^{-1}	35.7	49.1	61.7	29.1
Sediment yield	Ton ha^{-1}	2.5	7.4	23.4	3.0

Questions about connectivity of sediment transfers, the nature and distribution of erosion hotspots along channels are addressed in part through channel connectivity mapping, using the method described by Hooke (2003). This method is based on the interpretation of various morphological and sedimentological evidence. In this, the morphology of the channel is mapped, detailing variations in the dimensions of the channel bed and floodplain, bedrock exposures and the position of the check dam/groyne structures and road crossings. Particular attention is given to mapping the sources (gully/tributary, banks/valley walls) and storages of sediment (bar forms, accumulations behind check dams) along the channel. Using the combined map layers (channel morphology, sediment sources and storages) sediment source zones are identified and the channel is divided into areas of erosion, erosion and storage, transfer and net storage.

Check dams have been constructed throughout the Cárcavo catchment in an effort to reduce the erosion and transfer of sediments from incoming tributaries and along the main channel (Castillo et al. 2007). These check dams represent major breaks in the potential connectivity of sediment transfers through the catchment, with large amounts of coarse and fine-grained sediments stored immediately upstream of these structures. They also have a profound effect on patterns of erosion, transport and storage of sediment along the channel. Ten check dams were mapped along the main channel, in varying stages of infill. Road crossings over channels can also act as barriers to sediment transfers, having an effect similar to check dams.

The mapping and interpretation is exemplified in Fig. 2.10 for the upper part of Cárcavo channel. The channel has been divided into segments or reaches. Generalised patterns of potential connectivity can be described for Segments 3–8. A zone of erosion exists downstream of check dams. Within these reaches there is a reduction in the potential for sediment storage, this in part due to the trapping of sediments by the structure upstream and increased erosivity of flows immediately downstream, a product of the lack of sediment load. The channel immediately downstream from the check dam is often scoured to bedrock and there is a notable lack of sediments. Field observations of changes in the cross-sectional shape of the stream channel, the composition of channel bed material, and bankfull stage measurements indicated that the dams cause erosion downstream (Castillo et al. 2007). Where the channel traverses hardened marls, the channel is confined and entrenched to bedrock. Localised areas of scour result in patches of potential ponding that are

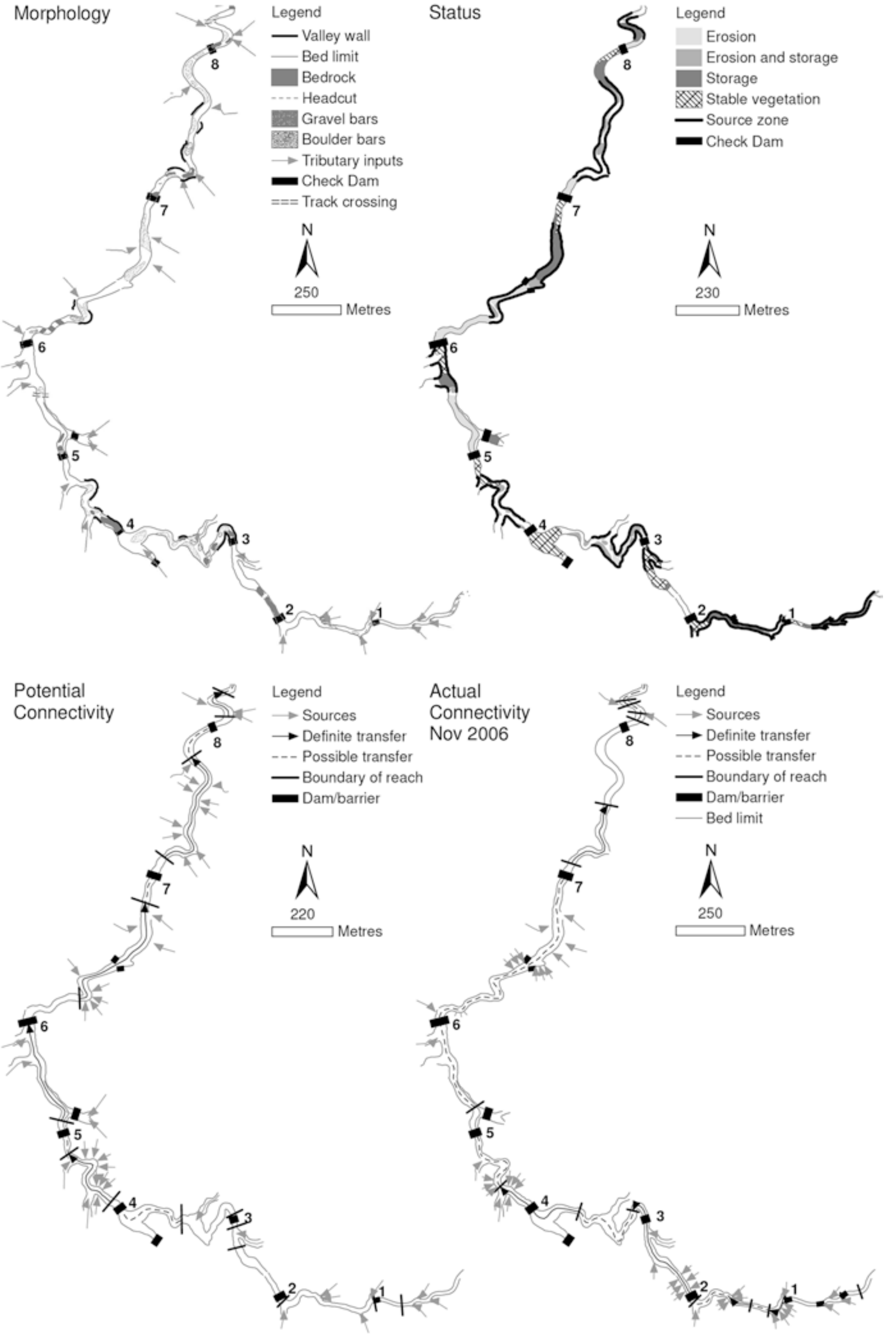

Fig. 2.10 Mapping and interpretation of morphology, status, potential connectivity and actual connectivity along the main channel of Cárcavo for the November 2006 event, upper Cárcavo, Southeast Spain (After Sandercock and Hooke 2011)

characterised by sparse reeds and grasses, which are likely to be frequently removed by floods and sediments flushed through. These reaches are classified as potentially highly connected.

A zone of aggradation extends upstream of the check dam, a response to the reduction in channel gradient. Coarse and fine-grained sediments accumulate upstream of these structures, forming temporary sediment storages. The accumulation of sediments and ponding of water behind these structures provide favourable conditions for the establishment of *Tamarix canariensis* and *Phragmites australis*. As a number of these check dams are completely filled with sediments, it is likely that there are sediment transfers beyond these barriers, however this needed to be confirmed by mapping of actual connectivity for an event.

The lower part of the Cárcavo channel lies more deeply entrenched within Quaternary alluvium and Marls. Based on mapping of sediment sources, it is clear that the majority of coarser material (gravels and boulders) in that part of the channel is being sourced from adjacent valley walls and not from incoming tributaries. Gravel bars form in sections where the channel is supplied with sufficient material from valley walls through mass failure mechanisms and direct erosion of walls by floods.

The 8 November rainfall event of 40 mm, generated sufficient runoff for flow to be recorded in the main channel. Peak stage varied from 0.47 to 0.76 m at different locations, with calculated flood discharge of 1.39–1.94 $m^3\ s^{-1}$ as calculated using WinXSPRO software. In the upper parts of the network where the channel has a simple rectangular-shaped morphology, the flow filled the channel floor and had an average depth of 0.3–0.4 m. In the lower reaches the channel has a more compound form, with a smaller inner and a larger outer channel. Flow filled the inner channel to an average depth of 0.5 m. The event had minimal impact on channel morphology and vegetation.

The event was of sufficient magnitude for transfers of sediment to extend beyond a number of check dams. Some tributaries did not contribute sediments to the channel. Of the 36 tributaries which adjoin the main Cárcavo channel, 15 (42 %) did not contribute sediments, whereas the remaining 21 tributaries (58 %) did contribute sediments to the channel. Those tributaries which did not contribute sediments had significantly larger drainage areas (Mean 82 ha) than those contributing sediments (Mean 24 ha). Connectivity mapping has highlighted that sediment inputs to the main channel from incoming tributaries and gullies are actually very low for the events documented. This is not surprising given the high number of check dams that are present throughout the catchment, but it was also not a high flow event. This is also supported by the connectivity mapping done at the land unit and subcatchment scale, which showed that, while there may be significant rilling in fields, the majority of eroded sediments are deposited in the agricultural landscapes at a point not far from the sediment source (within c.50–200 m). Many of the non-contributing tributaries were also highly vegetated in their lower ends. A large proportion of sediments transported along the channel are input directly from valley side walls. In larger catchments more opportunity arises for deposition, in the wider valleys. Also, in this type of environment only large rainfall events generate enough runoff to sustain connected flow through the catchment.

The following areas are identified as erosion hotspots in channels: incoming gullies; confluences; thalweg; areas downstream from check dams; steep valley walls.

2.4.5 Catchment

A method of assessing theoretical connectivity at the catchment scale for application within the modelling environment has been developed by Borselli et al. (2008). This section provides documentation on the equations used, theoretical connectivity maps and validation of these maps in the field. More detailed documentation on the application of theoretical connectivity to modelling is given in Borselli et al. (2008). Various applications and variants can be found in literature after 2010. (For a review please see: http://www.lorenzo-borselli.eu/presentations/Connectivity-SSOG-2015-Borselli.pdf).

The basic idea is that a given spot can be problematic for a series of reasons: (1) it is cut from upslope runoff and consequently does not receive enough water for plants to survive (water stress); (2) it is an excessive sediment/runoff source and contributes substantially to downslope problems (e.g., reservoir siltation, soil erosion). These problems can be managed, at least to a certain extent, if those hotspots are identified and the connection pathway is defined. This allows us to introduce the concept of ‘effective catchment’ which is the part of the catchment that is really connected to the particular hotspot (which can be the main drainage system as a well as a given field or part of it).

Reasons for disconnection are: (1) ditches, (2) segments of high infiltration rate (e.g. good vegetal cover); (3) area with rough surfaces (high storage capacity); (4) countersloping or large and scarcely sloping areas. The same factors also act for catching transported sediment. To them we can add: (5) any area with high Manning roughness (e.g. grass strips). In most cases of mitigating land degradation the aim is to decrease the connectivity and add connectivity breaks. Obviously, these connection-breakers have less chance to cut a flux the weaker the flux is and the longer the distance the material has to travel to get to a given spot. On this basis (and other more detailed and rigorous scientific bases) the following ratio was proposed as an index of connectivity of a given spot to another spot which is n steps downslope (one step = one cell of size d, gradient s_j and connectivity breaker factor F_j) while the up-slope catchment has an area A_{up} with mean slope $\overline{s}$ and mean connectivity breaker factor $\overline{F}$:

$$I = \log_{10}\left[\frac{\overline{s}\,\overline{F}\sqrt{A_{up}}}{\displaystyle\sum_{\substack{\text{over all downslope}\\ j \text{ segments}}} \frac{d_j}{s_j F_j}}\right] \tag{2.1}$$

Where:

$$F_j = CNi_j C_j = CNi_j * W_j \tag{2.2}$$

and where:

W_j is the general weighting factor that in Borselli et al. (2008) is equivalent to C factor in USLE-RUSLE models;

CNi_j is the SCS-curve number method:

Cni, $i=I$, II, III following antecedent moisture conditions.

F_j has been identified with the local curve number value (SCS-curve number method: Cni, $i=I$, II, III following antecedent moisture conditions) when dealing with runoff; and with USLE crop cover factor C. The product $F_j=Cni\ C$ has been used as sediment is connected only if water is connected. The Eq. 2.1 is a variant of the general formula proposed by Borselli et al. (2008) and in this case more oriented to both general runoff generation and potential water erosion. Examples of application to the Cárcavo basin are shown in Figs. 2.11 and 2.12.

The theoretical connectivity produced by the model required validation as suggested also by Borselli et al. (2008) An observation network was established at the end of summer 2006 (described under Reforested land, Sect. 2.4.2.1). A total of 58 plots were established, stratified by the connectivity value of the pixel. Some

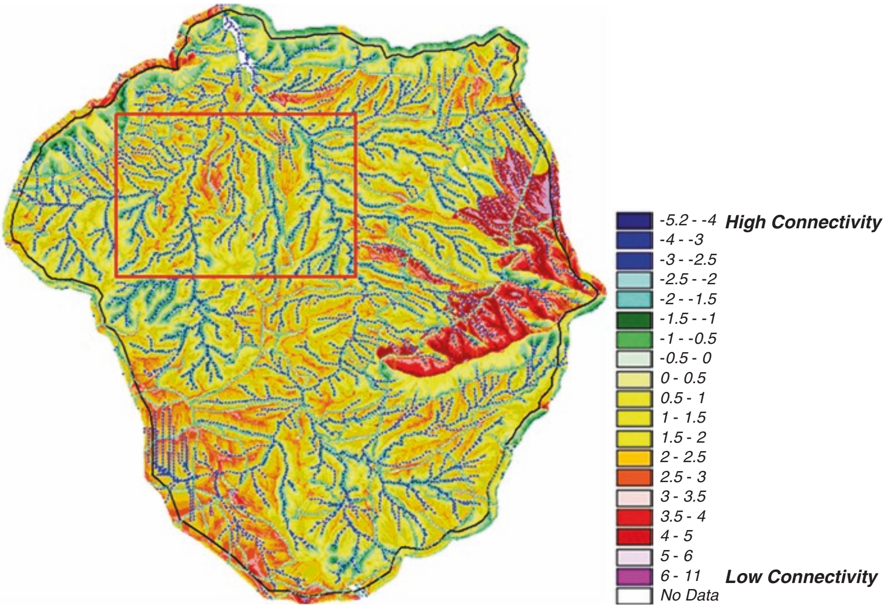

Fig. 2.11 Modelled connectivity (IC Index) for the whole Cárcavo catchment. The connectivity factor here is the product $F_j=Cni\ C$; The *rectangle* indicates the part of the catchment shown in Fig. 2.12

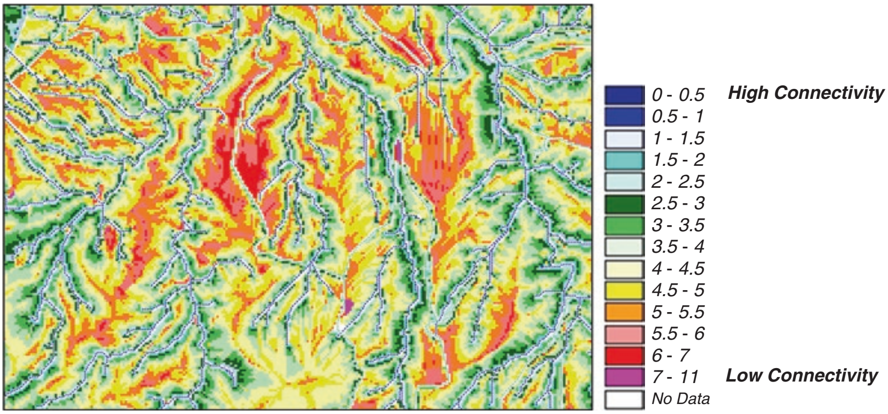

Fig. 2.12 Map of modelled sediment connectivity (IC index) for part of Cárcavo catchment shown in *rectangle* in Fig. 2.11

differences in amount of erosion and deposition were found between sites of different theoretical connectivity, with the very high connectivity sites particularly having greatest changes. In many of the papers now in literature the connectivity Index IC was geomorphologically validated in a variety of environments. (A full literature list can be found also at https://scholar.google.es/scholar?oi=bibs&hl=en&cites=8062253390937599926&as_sdt=5 as well as the papers indicated in Borselli 2015 presentation indicated above.)

2.5 Conclusions

This chapter has outlined the approach to assessing connectivity and exemplified the detailed techniques and the results at a range of scales and in a variety of land uses and settings. The methods developed enabled the identification of major patterns and pathways, erosion hotspots and factors contributing to vulnerability and risk of erosion. These have then been used in developing the spatial strategy to minimize connectivity, described in Chap. 5.

Studies have identified the important role of terraces in reducing potential connectivity, but that if they are not constructed correctly and maintained they may then form a point where erosion begins, their collapse then further enhancing connectivity. Mapping of connectivity in Reforested Lands highlighted that areas of erosion have a tendency to correspond with steep terraces that have a long talus and are partly deteriorated. Concentrated flow lines develop along defective terraces that are not completely perpendicular. Repeat studies of Cropland areas using aerial photographs (1956) and field surveys (2005) has shown that there have been significant declines in the number of terraces (36 %) and retention banks (28 %), with 54 % of terraces and 50 % of retention banks intact in 2005. These results highlight a clear increase in potential connectivity for these areas, with declines in conservation structures reflecting larger fields and probably related to the mechanisation of agriculture during the 50 year period.

Repeat connectivity mapping of subcatchments for a number of rainfall events has shown that many of the same erosion pathways are activated by successive events. Access ramps, tracks and dirt roads represent major source areas for sediments and hotspots where erosion occurs. Surprisingly, whilst significant erosion and runoff resulted from the November 2006 event, very little sediment eroded by overland flow reached the rambla (channel), most of the sediment being deposited on terraces or other relatively flat locations. Repeat checking of gullies/tributaries entering the channel after rainfall events has highlighted that sediment inputs from incoming gullies and tributaries are actually very low, partly a reflection of the high number of check dams but also of vegetation within some sections of channels. A large proportion of the sediments transported along the channel are input directly from valley side walls. Check dams have an overwhelming influence on channel connectivity, these forming major breaks for sediment transfers through the catchment. Significant erosion occurs downstream of these structures due to clearwater effects. However, over time these checkdams fill and thereafter fine sediment is transported but the check dam can act as a ‘waterfall’, enhancing erosion downstream and danger of collapse. The conclusions on pathways and hotspots are used in development of strategies in Chap. 5.