**ENHANCING CONNECTIVITY INDEX TO ASSESS THE EFFECTS OF LAND
USE CHANGES IN A MEDITERRANEAN CATCHMENT**

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ABSTRACT

In the Mediterranean region, the long history of cultivation is associated with significant changes in the original landscape. Agricultural intensification and subsequent land abandonment and reforestation have significantly affected the hydrological behaviour and connectivity patterns of hydrological systems. Thus, information on the spatial distribution of land use/cover is essential for monitoring the runoff response to interpret catchment hydrology. A medium-size catchment of the central part of the Ebro Basin (NE Spain), representative of Mediterranean mountain agroecosystems, was selected to assess the effect of land use/cover changes during the last few decades on the hydrological network of the catchment. To this end, a topography-based index, the “index of connectivity” (IC), was applied to assess the effects of land use changes from 1957–2010. The sediment connectivity was estimated using a geomorphometric approach to simulate how connectivity changes due to the different land covers. To improve this index, we used a combination of C-factor, rugosity index and the novel application of a total aerial biomass equation (TAB) over pine reforested areas as a weight factor. A high-resolution (1 x 1 m) DEM (Digital Elevation Model) was created by filtering and applying a multiscale curvature classification algorithm. The connectivity values show a decrease directly related to the ~71% decrease of agricultural land. Understanding landscape patterns, changes and interactions of human activities is essential for land management in Mediterranean agroecosystems.

KEYWORDS: Land abandonment, natural revegetation, connectivity, digital techniques, Mediterranean agroecosystems

INTRODUCTION

Sediment connectivity is the connected transfer of sediment from a source to a sink in a system via sediment detachment and sediment transport, controlled by how the sediment moves between all geomorphic zones in a landscape (Bracken et al., 2015). Sediment connectivity has an important effect on the development of morphological landform features, being one of the greatest conditioning factors on the development of hydrological networks. Sediment connectivity has a major influence on how sediment is moved and relocated, modifying the current landscape, and determining the spatial distribution of sources and sinks of water (Puigdefabregas et al., 1999).

Highly linked to hydrological and sediment connectivity are the terms geomorphic or landscape sensitivity and coupling, introduced by Brunsden and Thornes (1979), and recently recovered by Fryirs (2016). Geomorphic or landscape sensitivity refers to how geomorphic systems respond to environmental change, i.e. the ability of the system faced with external interference to withstand the change. This term is suitable to categorise how agricultural activities disturb the system and how it reacts over subsequent decades. Furthermore, coupling is used within the context of the effectiveness of the transfer of sediment between the components of a fluvial system (Harvey, 2001) at a relatively small scale (Faulkner, 2008).

Studies have devoted increasing attention to the connection between areas with different hydrological behaviour and land use, with particular focus on the connection between hillslopes and channels (Borselli et al. 2008; Vigiak et al. 2012) and modelling the different processes of hillslope instability (Heckmann & Schwanghart, 2013). In addition, an interpretation of sediment transport by runoff and the associated soil erosion processes requires a background knowledge and the determination of water pathways to determine the location of the most probable sources and targets/sinks in the catchment.

Since the 1950s, agriculture in European Mediterranean agroecosystems was commercialised through technological developments and the EU common agricultural policy (CAP). There is a main environmental issue behind these policies, which favours the rapid expansion of certain management systems; crops have increased productivity and the agricultural activity has become more focused on more fertile and accessible land.

This resulted in a transformation of traditional agricultural practices toward intensive farming. In many areas, this produced a major decline in traditional labour intensive practices, becoming mountain agriculture catchments in marginal agricultural land (Lasanta et al., 2016). The problems that these trends have created are particularly marked in mountainous areas and in regions where agricultural land is generally found under unfavourable environmental conditions, such as high elevations, steep slopes, shallow soils and dry climatic conditions (MacDonald et al., 2000). In Spain, land abandonment has notably increased since the 1960s as a consequence of complex socio-economic and environmental changes, leading to depopulation of rural areas and the impossibility of mechanisation in steep terrain (Quijano et al., 2016). In addition, subsequent reforestation during the 1970s and 1980s caused a large impact on runoff and connectivity reduction due to vegetation growth (Buendia et al., 2016), but also increased forest fires (Royo et al., 2015). At present, the loss of steep slope agriculture and the search for more propitious agricultural lands are reducing runoff in mountain catchments, but also lead to abandonment of rural communities.

Over the last few centuries, steep slope areas in the Mediterranean region have been gradually transformed into terraced arable lands with an intensive impact both on the original soil and landscape. As a consequence of these changes, agricultural soils have

been modified: at present, they have different soil properties compared to their previous and original conditions (Romanyà & Rovira, 2011).

Soil erosion and hydrological connectivity are greatly responsive to land use (García-Ruiz, 2010; Mohammad & Adam, 2010; Nunes et al., 2011; Mohawesh, 2015; Keesstra et al., 2016). Mankind rather than natural forces is the source of most contemporary changes in land cover (Meyer & Turner, 1994). Agricultural deforestation and most land use changes have generally been considered as a local environmental issue, but at present it is becoming an important global problem (Foley et al., 2005). Soil erosion is directly related to the loss of soil nutrients in the topsoil resulting in soil degradation, which in turn leads to reduced soil productivity and increased soil erodibility (Novara et al., 2016; Quijano et al., 2016). Moreover, depletion of soil depth in agroecosystems can be a serious threat to agricultural sustainability (Fornes et al., 2005).

Steep slope agriculture has changed connectivity and erosion rates during the last few centuries in Mediterranean landscapes. Both coupling and sediment connectivity have to be viewed with regard to the temporal scale, ranging from the event timescale for hillslopes and channel coupling, to geological timescales for morphological changes in large basins (Heckmann & Schwanghart, 2013). Together with land abandonment, the subsequent continuous expansion of natural forest and revegetated areas is clearly affecting runoff amount and streamflow yield (López-Moreno et al., 2011). It has also been suggested that during vegetation development, soil heterogeneity increases, thus playing an important role in infiltration processes (Cammeraat et al., 2010). Furthermore, changes in water yield are associated with an increase in continuous temperature due to Global Warming and the subsequent increase in evapotranspiration rates from natural vegetation (Martínez-Fernández et al., 2013).

A temporal approximation is essential to quantify the vegetation increase induced by the abandonment of agricultural lands, the introduction of reforestation with pines and the loss of extensive farming over the hillsides. Our objective is to assess the variation of connectivity produced by land cover changes during the last 50 years over a Mediterranean catchment representative of mountain agroecosystems that have experienced intensive land abandonment and reforestation during the past century. The innovative characteristic of this investigation is quantifying the connectivity changes over time, as Foerster et al. (2014) tested with remotely sensed data, and adapting a connectivity index in the study area. This adjustment could be extrapolated to most steep slope agriculture areas. Moreover, we also try to model how connectivity varies in pine-reforested areas using total aerial biomass data (TAB) for a better understanding of the hydrological network functioning within reforested areas. A clear understanding of connectivity is essential for further development of soil redistribution models and to predict the future evolution of catchments.

MATERIALS AND METHODS

Study Area

The study area is included in the Arba river drainage catchment. The Barué's catchment (23 km²) is an ephemeral stream catchment located in the central part of the Ebro Basin in northeast Spain (Figure 1). From a geological point of view, it is situated on the distal part of the Pre-Pyrenean range with characteristically S-SW low bedding between 5–8°. The rock outcrops include two concordant Oligomiocene lithostratigraphic units of the Uncastillo Formation composed of sandstones, claystones and siltstones (Sole et al., 1972; Teixel et al., 1992; Pardo et al., 1996). The geomorphological setting is clearly

conditioned by the low bedding of the strata. This sets up the path of the streams following the strata dip.

The climate is continental Mediterranean, characterised by cold winters and hot and dry summers. Rainfall events mainly occur in spring (April and May) and autumn (September and October) and a summer drought between the two humid periods. The mean annual temperature is 13.4 °C and the mean annual rainfall is about 500 mm. Most abundant soils were classified during field surveys as Calcisols and Cambisols (FAO, 2014). The soils developed on Quaternary deposits are mainly formed by alluvial deposits and have basic pH, low soil organic carbon contents (between 0.13–5.65%) and the secondary accumulation of carbonates.

Multi-temporal analysis

The assessment of sediment connectivity was carried out by applying a topography-based index in two different scenarios using two land use maps for 1957 and 2010. The first map was created by orthorectification of the 1957 American army aerial photographs using a supervised classification in ERDAS after photographic enhancement. The actual map was digitised over 2010 PNOA (National Plan of Aerial Orthophotography) orthophotography and fieldwork maps.

The streams with higher connectivity ratios were digitised over 2010 orthophotography, and the connectivity index created with the 2010 DEM and compared with the 1957 aerial photography drainage net to visualise whether a remarkable displacement or modification in the slopes occurred between both periods (Figure 2).

Stream displacement and topographic changes between the periods can only be measured for what it is visible in the multitemporal aerial photography due to the absence of the 1957 DEM. Figure 2 shows the near-absence of displacement or modification of the secondary slope streams in a highly degraded area of the catchment. Most visible differences between both streams in Figure 2 are produced for the aerial stereoscopic photography deformation. These low grades of displacement in the secondary streams imply that most changes in the topography are below the detection limit of our DEM.

However, the main channel has variations in its morphology, being higher in the medium and lower parts where sections are deeper and surrounded by crop fields, and nearly insignificant in the upper parts of the catchment. Due to the impossibility of obtaining a 1957 DEM and after checking the absence of substantial modifications to the topography between 1957 and 2010, it was decided to use a 2010 DEM with a low grade of uncertainty.

DEM refinement

Nowadays, the most popular connectivity index from Borselli et al. (2008), the modified version by Cavalli et al. (2013) as well as geomorphological studies related to slopes or erosion (Kawabata & Bandibas, 2009; Gutiérrez & Lizaga, 2016; Masselink et al., 2016) are based on DEMs. Thus, the accuracy of model results is fully dependent on DEM quality and resolution: it is needed to apply and develop a topography-based index such as IC correctly. Therefore, developing a model based on LIDAR data was necessary to refine the existing LIDAR points to create a high-resolution DEM (1 x 1 m). Accordingly, we used IGN (Spanish National Geographic Institute) raw LIDAR data points following Montealegre et al.'s (2013) methodology. First, we deleted the noise of

the data, deleting LIDAR points classified as noise using ArcGIS. Secondly, we proceeded to filter our LIDAR data in order to generate a bare ground 1 x 1 m raster DEM using MCC-LIDAR, a command-line tool for processing discrete-return LIDAR points in forested environments based on the Multiscale Curvature Classification algorithm developed by Evans & Hudak (2007). The root mean square error (RMSE) was calculated for both DEMs using a cross-validation method (Table 1).

Total aerial Biomass (TAB)

LIDAR data represent a tool that supports the calculation of forest inventories and allows the vegetation to be measured in three dimensions (Ruiz, 2012; Reyes & Delia, 2014). Total aerial biomass (TAB) was calculated for the reforestation forests using Equation (1) developed by Domingo (2016) and the software FUSION. This equation was created and optimised in a nearby reforested area with *Pinus halepensis* Mill that had similar forest dasymetric characteristics as the pine reforestation in the study catchment. Equation (1) is a good complement to understand the change produced by pine reforestation.

$$TAB\left(\frac{\text{kg}}{\text{ha}}\right) = e^{(0,0158*A2m)} * e^{(0,0713*P40)} \quad (1)$$

Domingo (2016)

where e refers to the Euler's number, $A2m$ is the percentage of the first LIDAR laser return above 2 m ground height, produced by the reflectance of the treetop canopy, and $P40$ is the 40th percentile of LIDAR data. A 25 m x 25 m/pixel size was selected to create

a raster image comparable to the study plots accomplished by Domingo (2016) to obtain such an equation.

Connectivity index and adaptation to steep slope agriculture

In headwater fluvial catchments, the more relevant aspect of coupling is the connection between hillslope and channel, i.e. hillslope-channel coupling (Harvey, 2002). Sediment connectivity was estimated using a geomorphometric approach to simulate how connectivity changes due to different land covers. Hence, it is very important to determine how the system connectivity responds to human-induced cover changes (Harvey, 2002). For this reason, we applied the connectivity index (1) proposed by Borselli et al. (2008) using the C-factor from RUSLE (Revised Universal Soil Loss Equation) as a weight factor (W) in the index.

$$IC = \log_{10} \frac{D_{up}}{D_{dn}} \quad (2)$$

Where D_{up} and D_{dn} are the upslope and downslope components, defined by:

$$D_{up} = \overline{WS}\sqrt{A} \quad (3)$$

where W is the average weighting factor of the upslope contributing area, S is the average slope gradient of the upslope contributing area (m/m) and A is the upslope contributing area (m²).

$$D_{dn} = \sum_i \frac{d_i}{w_i s_i} \quad (4)$$

where d_i is the length of the flow path along each i cell according to the steepest downslope direction (m), and W_i and S_i are the weighting factor and the slope gradient of the i cell, respectively.

Borselli et al. (2008) proposed $S = \sin \alpha + 0.005$ including 0.005 as the minimum slope value to avoid infinite values in Equation (4). Thus, we preserved the original values of our 1 x 1 m DEM to obtain more realistic results after checking the absence of 0 slope values. Besides calculating the contributing area, we used the procedure of multiple flow D-infinity approach (Tarboton, 1997) instead of the single flow direction algorithm (O'Callaghan & Mark, 1984) used in the hydrology ArcGIS toolbox as proposed in Cavalli et al. (2013). Using D-Infinity allows us to calculate the flow accumulation of converging and diverging flow directions to create a more realistic topographic index.

In addition, the connectivity index was improved by using a terrain roughness index as a weight factor. Cavalli and Marchi (2008) and Cavalli et al. (2013) developed and later implemented a roughness index (RI) in the connectivity index. RI was calculated as the standard deviation of the residual topography using the mean of the 25 neighbourhood cells values as a 5 x 5 moving window. However, for our index, we created a new roughness index (SdRI; Equation 5) calculated as the standard deviation of the slope as recommended by Grohmann et al. (2011). SdRI was also applied using a 3 x 3 moving window to accentuate steep slope terrace characteristics of the low strata bedding preserved and modified by agricultural practices in our study catchment.

$$\sigma = \sqrt{\frac{\sum_{i=1}^9 (x_i - x_m)^2}{9}} \quad (5)$$

Where x_i is the pixel value and x_m is the average of the 3 x 3 moving window.

Figure 4 shows the good adjustment of the SdRI to the steep slope terraces compared to the RI, which also shows a good fit, but appears to be better for larger terraces than those present in our study area.

Furthermore, in Equations (2) and (3), we also used our two land use maps (C-factor) as weighting factor to show the differences between both land uses (1957 and 2010) and how the connectivity index changed over time. The C-factor values assigned to our land uses are 0.0011, 0.0010, 0.06, 0.2 and 0.26 for reforestation forest, Mediterranean forest, abandoned land, cultivated land and trails respectively extracted from Panagos et al. (2015). Combining both approximations, a weighting factor was applied as the link between the C-Factor and SdRI index, trying to develop a better adjustment to reality. The model was tested in the entire catchment to facilitate visualisation at a more detailed scale in an area where the four land uses occur. We selected the same area as the red square of Figure 1 to show how connectivity changed over 50 years due to land use and cover variations.

To introduce the probable variations of forest density in our model, the TAB layer created in the previous section was implemented inside the C-factor layer using it as the inverse of TAB to produce lower C-Factor in the areas with higher densities, and higher C-Factor in the areas with lower densities. Even with a 1 m resolution DEM, it was impossible to implement the same methodology for the other land covers: it was only used on reforested areas by creating a mask layer.

$$W = (C * \frac{1}{TAB}) * SdRI \quad (6)$$

where W is the weighting factor, C is the C-factor of the different land covers, TAB is the variance of the total aerial biomass (only used over pine reforestation) and SdRI is the roughness index. These data are normalised by scaling them between 0 and 1. This normalisation is needed because the weight factor is a dimensionless factor and should range from 0 to 1 to be weighted equally to slope in the index. For this reason, the W factor was normalised using unity-based normalisation Equation (7):

$$Z_i = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (7)$$

Where x_i is the pixel value and $\min/\max x_i$ are the minimum and maximum values, respectively, of the moving window.

RESULTS AND DISCUSSION

Digital Elevation Model

Increasing DEM quality allowed a significant improvement in the accuracy of the connectivity model. Without a good enhancement and a high-resolution digital terrain model, the possibilities of terrain error or the lack of reality adjustment increase exponentially (Li & Wong, 2010; Vaze et al., 2010), therefore increasing the error of the connectivity index. Thus, enhanced LIDAR data over regular IGN filtered LIDAR data allowed us to create a more accurate 1 x 1 m high-resolution DEM instead of the 5 x 5 m resolution IGN DEM. Figure 3 compares the hillshade created using IGN and MCC filtered data, both compared after increasing resolution to 1 x 1 m. Table 1 shows the

RMSE reduction in MCC DEM and also how RMSE increases with higher vegetation canopy density and height.

Even increasing the resolution of the IGN DEM with their filtered data, there was a high adjustment error regarding the vegetation; but this error was greater in scrubland and riparian vegetation than in forests. In the Figure 3 LIDAR profiles, it is clearly visible how the MCC filter DEM (B) successfully removed the scrubland points situated in the upper part and in the middle part of the profile, unlike the IGN DEM (A), which is clearly visible in the hillshade image. For this reason, the DEM optimised with MCC-filtered data was selected (Figure 3).

Land use distribution maps

Numerous studies in a variety of environments have demonstrated the significant effects of the vegetation cover increase on the reduction of runoff connectivity and water erosion (Elwell & Stocking, 1976; Zuazo & Pleguezuelo, 2008; Mohammad & Adam, 2010; Sandercock & Hooke, 2011; Fox et al., 2012). The importance of land cover can be summarised in two main effects: the direct physical protection of the soil surface by the canopy and leaf cover preventing rainfall impact and soil detachment particles, and the indirect improvement of the soil resistance and quality (García-Ruiz et al., 1995; Boix-Fayos et al., 1998; Dunjó et al., 2004, Navas et al., 2008).

The high variation in total runoff and consequently in transported sediment reflects the major importance of total land cover and land use type on runoff generation and soil loss; these have significant implications on soil erosion (Kosmas et al., 1997). The results

obtained for the 1957 and 2010 land cover maps reveal the major variation that took place during the last five decades in the study area.

Our results showed that Mediterranean forest and grassland have been the main land uses in the catchment over the years, together accounting for more than 50% of the total catchment surface area. A decrease in cultivated land was observed between 1957 and present, when the area dedicated to agriculture decreased from 13.4 to 3.8 km² (corresponding to a decrease of ~71%; Table 2). On the other hand, forested areas increased from 9.2 km² in 1957 to 15.8 km² at present. Vegetation and land use are important factors on the catchment hydrology; as indicated by Bryan & Campbell (1986), both are key controls on the intensity and frequency of runoff and surface sheet erosion.

Figure 5A shows a classic example of steep slope agriculture with almost 70% of the slopes and stream terraces cultivated. Conversely, Figure 5B shows an important modification caused by natural revegetation and reforestation over steep slopes. It has been shown in a nearby large mountain catchment that badlands and severely eroded areas have higher connectivity values than agricultural, forest and scrubland land uses/covers (Palazón & Navas, 2014).

Steep slope terraces are common in Mediterranean mountain agroecosystems for rudimentary agriculture. The near-absence of tectonics in the Barués catchment determined the low-dip strata, resulting in an easily farmable terrain. Steep slope agriculture not only increases erosion and runoff ratios on the hillslopes, but also produces slope instability, fostering the probability of mass movements due to the absence of vegetation cover that protects the soil from erosion and prevents its displacement. This can be seen in Figure 6, which shows a typical rotational stream-bank failure movement. These types of landslides are usually developed during storm events on poorly cohesive

materials favoured by the absence of vegetation cover, high slope and dryland crops situated on the top of the hills of the catchment. These small slide movements are developed on stream walls induced by erosion at the toe of the stream bank walls.

Quantification of riparian vegetation over time was difficult due to image resolution, but a minimum 10% increment was detected. The presence of riparian forest and the reinforcement of bank soils by herbaceous riparian vegetation significantly reduce the likelihood of erosion by mass failure, in agreement with the observations of Hubble et al. (2010). Moreover, riparian vegetation increases the apparent cohesion through root reinforcement of bank soils reducing bank migration rates, increasing bank strength and reducing bank failure frequency (Micheli & Kirchner, 2002).

Total aerial biomass (TAB)

The Barué Catchment TAB was divided into three major groups with distinctive ranges of TAB values (Figure 7). These three groups coincided with the three different reforestation forests periods (MOP-CHE, 1976; Ortigosa et al., 1990) that conditioned the greater or lesser development of trees and forest. The three groups reported distinctive ranges of TAB values; thus, higher values were found on north faces and lower ones appeared on south-facing slopes (Figure 7). Nevertheless, younger reforestation was too minor as to test this assumption with TAB values. Table 3 shows major differences between the three different pine forests (Rf 1, Rf2 and Rf 3). The oldest (Rf 1) nearly doubled the mean value of the total aerial biomass, while Rf 2 doubled the youngest one (Rf 3). The TAB mean values of the north-sloping faces (WNW-ENE, 292.5–67.5°) in contrast to the mean values of the south-sloping faces (WSW-ESE, 112.5–247.5°)

calculated for each pine reforestation showed substantial differences. The solar angular ranges, being higher on the south-facing slopes, increasing temperature and reducing the accumulation of moisture, regulate this effect. Hence, the less developed soil biological activity and the lower organic matter content probably affect tree growth (Cerdà, 1998).

The TAB equation is a good complement in the model to understand the change produced by pine reforestation, not only related to coupling and connectivity but also to the increment of the vegetation volume. This increment probably reduced greenhouse environmental effects, as Fang et al. (2001) observed in China, suggesting that carbon sequestration through forest management practices could help offset carbon dioxide emissions.

Connectivity index

With the modification in land cover, mostly in reforested areas, the decrease of runoff might interfere, reducing sediment displacement and probably concentrating highest connectivity and erosion areas in streams that remain coupled, as can be seen in the yellow-green streams within the reforested areas in Figure 8.

The connectivity index with different land covers as a weight factor gives an approximation of the effect of human activity over the study area. In Figure 8, the decrease in water and sediment fluxes can easily be recognised due to new covers such as natural revegetation, abandoned fields and the great variation induced by reforestation (Table 4).

The decrease of IC values could be related to the increase in trees and vegetation cover, which minimises the kinetic energy of the raindrops preventing soil detachment (Llorens,

1997; De Luna et al., 2000). Hence, vegetation cover probably improves soil quality, by favouring infiltration and preventing runoff. On the contrary, high erosion rates and low slope resistance could easily produce topless and landslides as the most frequent mass movements (Figure 6). These feed large volumes of sediment into the stream system, as topless and bank failures are found in most stream banks along the principal streams in the catchment.

Implementation of SdRI gives greater relevance to the steep slope terrain adapting IC model to Mediterranean mountain agroecosystems. This is clearly visible on the top hills, and also produces little decentralisation of the hydrological network caused by the alternating flat-steep slopes produced by the combination of ancient agriculture terraces and the strata (Figure 8). In addition, the TAB layer provides a real variation inside the pine reforestation, showing the difference between biomass, and also proving that vegetated soils situated on the north-facing slopes had greater biomass. Higher proportions of biomass surely result in more developed soils and probably lower sediment yield, runoff and erosion; while bare soils on the south-facing slopes might have higher runoff rates.

The implementation of different land uses (C-factor) in the model shows the relevance of reforestation areas to the development of hydrological connectivity. Reforestation seems to be homogenous, but has variations in above-ground biomass density inside reforested areas due to different factors such as topography, solar radiation and organic matter among others. Figure 4C shows the variation produced for the inclusion of the C-factor and TAB layer in the *W* factor over the roughness index, including the variation of the vegetation cover.

Figure 9 shows the zoomed biomass variation introduced into the IC index with the TAB layer. The connectivity decline is clearly visible on the north faces in relation to the other orientations. This is probably due to the distribution of soil-moisture not only in the reforested areas, but also in other areas because of the patchy vegetation structure (Marchamalo et al., 2015).

Comparing both IC output maps, land cover maps (Figures 5 and 8) and IC values (Table 4), the importance of land cover for preventing runoff can be seen, as well as the benefits of landscape restoration. Strong changes in reforestation cover, land abandonment, natural revegetation and especially the reversal to Mediterranean forest probably have major effects on the loss of coupling and, as a consequence, on the decrease of discharge, as Navas et al. (2011) observed in the Yesa reservoir (and probably also the streamflow reduction, as observed by many authors across the Iberian Peninsula: Morán-Tejeda et al., 2010; Lorenzo-Lacruz et al., 2012). Other authors have also reported runoff reduction as a consequence of the increase of infiltration, interception and evapotranspiration rates. Furthermore, Table 4 confirms that the highest connectivity changes are produced between the actual pine forest and the same area in 1957; this also occurs, although to a lesser extent, over the natural revegetated forest.

CONCLUSIONS

Land use/cover changes by human intervention during the 1960s, mostly due to tillage, have increased connectivity, thus intensifying natural geomorphological processes such as landsliding, gullyng, incised streams and severe soil erosion.

The revegetated abandoned lands and reforested areas have been shown to be very efficient in reducing connectivity. Naturally revegetated areas have decreased the

connectivity, thus probably limiting soil erosion. Pine reforestation has produced a clear increase over aerial biomass, probably enriching soil organic matter in the reforested areas of the catchment. The increase in biomass could be extrapolated to the other land covers in the catchment. Despite other naturally revegetated areas being likely to experience similar gain in biomass than reforested areas, it has not been possible to estimate it using LIDAR techniques, because at present the equation has still not yet been developed for such vegetation covers.

Soil maps with a high level of accuracy are a good approximation; yet even improving DEM quality to 1 x 1 m and aerial photograph enhancement was not enough to show changes in the riparian vegetation between study dates. In future research, it will be necessary to estimate the channel variation to assess at lower scales how this variation has affected changes in connectivity. The implementation of SdRI roughness index and Total Aerial Biomass improved both topography and vegetation cover features, increasing the quality and adjustment of the connectivity index. Model enhancement with a 1 x 1 m high-resolution DEM, D-Infinity, SdRI roughness index and Total Aerial Biomass is important to understand the hydrological behaviour of agricultural mountain catchments.

The connectivity index developed here is probably a good approximation to the reality in this area, emphasising that anthropogenic activities are nowadays the greatest landscape modifiers. Moreover, this index represents a good approximation to the temporal connectivity variation in Mediterranean agricultural catchments, and has the potential to be used for ecological purposes, future soil management and for field survey studies.

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TABLE 1. *RMSE calculated for both DEMs over the entire study area and over the different land uses: MCC (Calculated using MCC algorithm) and No MCC (Regular filtered algorithm)*

	Agricultural		Forest		Pine		All catchment	
	MCC	No MCC	MCC	No MCC	MCC	No MCC	MCC	No MCC
Mean	0.062	0.177	0.151	0.390	0.235	0.424	0.132	0.312
Max	0.643	1.210	0.860	1.572	0.350	1.630	0.671	1.439
Min	0.002	0.001	0.005	0.001	0.012	0.022	0.005	0.005
SD	0.100	0.130	0.218	0.137	0.325	0.681	0.192	0.243

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718 *TABLE 2. 1957 and present land use/ land cover measures and their representative*
 719 *percentages of the total catchment area.*

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Land use/land cover	1957 Land use map		2010 Land use map	
	Square kilometers	% of the total area	Square kilometers	% of the total area
Cultivated	13.42	58.2	3.81	16.5
Mediterranean forest	9.23	40.0	11.49	49.8
Reforestation forest	-	-	4.36	18.9
Abandonment agriculture	-	-	2.93	12.7
Riverbank vegetation	0.40	1.8	0.46	2.0

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738 TABLE 3. *Rf 1, 2, 3 (Reforestation forest) show Min, Max and Mean values of tons per*
739 *ha, total TAB an area of three different forest ages.*

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	Pixel(25 x 25m) Value tons/ha			Mean pixel values		Total Area	
	Min	Max	Mean	N, NW, NE faces	S, SW, SE faces	BT value	ha
Rf 1	35.1	182.9	109.4	110.7	94.5	104151.8	70
Rf 2	13.7	121.5	52.0	56.6	49.1	287201.5	358
Rf 3	9.7	33.6	21.9	36.6	26.7	1434.7	5
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TABLE 4. *Connectivity values over land uses in 2010.*

2010 Land Use	Agricultural	Forest	Pine	Abandonment	Global
1957					
Min	-9.6	-9.6	-9.5	-9.59	-9.578
Max	2.31	2.25	1.95	2.29	2.254
Mean	0.2	0.11	0.16	0.11	0.1
2010					
Min	-10.6	-10.4	-11	-10.1	-10.496
Max	1.8	1.9	1.6	1.76	2.08
Mean	-0.17	-0.35	-0.96	-0.26	-0.322

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