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Modelling the effects of land use changes on runoff and soil erosion in two Mediterranean catchments with active gullies (South of Spain)

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Abstract: This study investigates the effects of land use changes between 1956 and 2006 on runoff and soil erosion in two Mediterranean catchments (South Spain) with active gullies, by applying the RMMF Model and by comparing the erosion channel network from both years. Results underline the complexity of soil erosion dynamics in gullied catchments where a general increase in soil erosion due to land use changes can occur simultaneously with a decrease in erosion rates within the gully system.

Keywords: gully erosion, land use, RMMF model, runoff, soil erosion

Introduction

Gully erosion represents an important soil degradation phenomenon in Mediterranean environments (Poesen & Hooke 1997). Several recent studies have approached the impact of gradual or sudden changes in land use and exploitation systems on the initiation and development of gullies (Poesen et al. 2003, Gómez-Gutiérrez et al. 2009, Martínez-Casasnovas et al. 2009). For instance, in southern Spain, Faulkner (1995) related the expansion of almond orchards with the increase of gully density. Changes in land uses can modify the gully activity from a morphological and hydrological point of view, leading to an increase of soil erosion intensity (Oostwoud Wijdenes et al. 2000, López-Vicente & Navas 2009a) or conversely reducing the presence of gullies due to either their suppression by the forest machinery or their colonization by vegetation (Morgan 1979, Rey 2003). Reforestation usually promotes soil stabilization in various ways (e.g. vegetation in gully channels trap sediments). Land abandonment or intense ploughing can intensify gully erosion processes whereas filling up of the gullies by farming machinery in cropland promotes short-term decrease of their activity but higher rates of soil loss in the long-term (Gordon et al. 2008). This work seeks: i) to compare the gully network in 1956 and 2004 in two Mediterranean catchments with similar physiographic, climatic conditions and historical land uses but with different land use evolution in the last century; ii) to assess the different topographic thresholds for gully initiation for different land use scenarios; iii) to estimate the hydrological and erosion behaviour of these catchments by applying a modified version of the RMMF model; and iv) to discuss the feasibility of the selected model to quantify the effect of land use changes on soil erosion rates in catchments with active gully systems. Results of this work will be of interest to analyze the effect of land use changes on gully dynamic under Mediterranean conditions and to define some of the current cutting-edge topics in modelling water soil erosion by sheet, rill and gully processes at catchment scale.

Study area

Two similar catchments were selected in Southern Spain (“Montes de Málaga” – Betic Cordillera): the Melgarejo (ME, 150 ha; altitude from 655 to

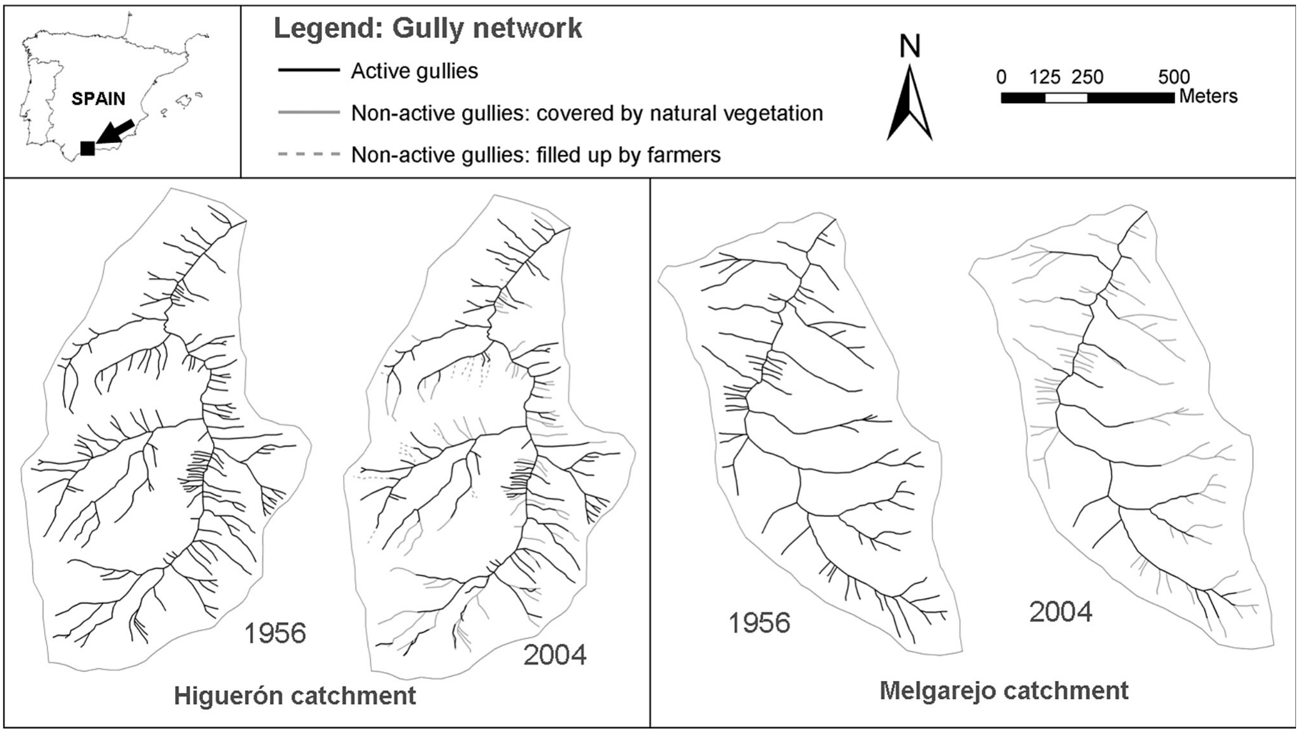

Fig. 1. Location of the study area in south Spain and drainage gully networks of the two study sites in 1956 and 2004

1,032 m a.s.l.) and Higuerón (HI; 166 ha; altitude from 575 to 1,012 m a.s.l.) catchments (Fig. 1). Topography is characterized by hillslopes with steep gradients (>25%) and convex profiles. Geology comprises Paleozoic metamorphic rocks (shales and phyllites) and relief is dissected in deep valleys due to the incision of the drainage network during the Plio-Quaternary. The average annual precipitation is 692 and 629 mm, at ME and HI, respectively. Both catchments shared a similar land use evolution until 1930s: deforestation at the end of the Middle Ages, cultivation of mainly vineyards, almonds and olives till the end of 19th century, and partial land abandonment due to the agricultural crisis in the first half of the 20th century. As a consequence the hydrologic and erosive dynamic changed: extreme rainfall events induced gully erosion and serious floods affected Málaga city. To reduce these problems, a reforestation programme was executed but only ME was treated. Table I summarizes significant land use changes that occurred in ME, whilst HI continued evolving according to the needs of the land owners. ME has become a completely forested catchment with pines as the main cover type. Although HI was mainly an abandoned land in the 1950s, it evolved in a more complex way than ME: some abandoned fields were cultivated again due to the expansion of almond orchards in the 1970s and the access to modern machinery, grazing land has been progressively reduced to some areas of the catchment whereas other areas remain abandoned and increasing their vegetation cover due to the favorable climatic conditions for vegetation recovery.

Methodology

Several field surveys were carried out and more than 100 representative soil samples were collected within the two catchments. Gully systems and land use changes were mapped using aerial orthophotos from 1956 (Excma. Junta de Andalucía Government) and 2004 (Excma. Diputación Provincial de Málaga Government), and geographic infortation system (GIS) techniques. The mapped gully system and the different land uses for 2004 were controlled by means of a field survey. Related to drainage network, some parameters were obtained to characterize both catchments: Horton hierarchy, total length, drainage density, upslope contributing area at the head of the gullies and slope steepness at the gully initiation. A modified version of the revised Morgan, Morgan and Finney (RMMF) model (Morgan 2001) was used to estimate the runoff volume per raster cell, the effective cumulative runoff and annual soil loss by sheet and rill erosion.

This model is semi-physically based and estimates the rates of soil detachment by splash (F; Mg ha^{-1} yr^{-1}) and runoff (H; Mg ha^{-1} yr^{-1}) and compares the total rate of detachment with the runoff transport capacity (TC; Mg ha^{-1} yr^{-1}) to calculate the values of soil loss (E; Mg ha^{-1} yr^{-1}):

$$E = \min\{(F+H), TC\} \tag{1}$$

$$F = K \cdot E \cdot 10^{-2} \tag{2}$$

$$H = Z \cdot CQ_{eff}^{1.5} \cdot \sin S \cdot (1 - GC) \cdot 10^{-2} \tag{3}$$

$$TC = C \cdot PCQ_{eff}^{\;2} \cdot \sin S \cdot 10^{-2} \qquad (4)$$

where K (g J^{-1}) is soil erodibility, E (J m^{-2}) is the total rainfall energy, Z (kPa^{-1}) represents the resistance of the soil, CQ_{eff} (mm) is the effective cumulative runoff, S (radian) is the slope steepness, GC (%) is the percentage of ground cover (crop residues and rocks), and C and P are the crop management and the support practices factors of the RUSLE (Renard et al. 1997) model, respectively. In this work the *RMMF* model is applied with the modifications proposed by López-Vicente & Navas (2009b) to consider the effect of cumulative overland flow, soil infiltration and microtopography:

$$CQ_{eff} = (CQ_0 - K_{fs} - SS_{\max}) \cdot \sin S \qquad (5)$$

where CQ_0 (mm) is the potential cumulative runoff, K_{fs} (mm day^{-1}) is the saturated hydraulic conductivity of the different soil types, and SS_{max} (mm) is the maximum soil surface storage capacity. Rainfall becomes overland flow after the topsoil is saturated and strongly depends on the distribution of rainfall and soil properties. The *RMMF* model computes the annual volume of runoff per raster cell (Q; mm) assuming that runoff occurs when the mean rain per erosive rain day (R_0; mm) exceeds the soil moisture storage capacity (R_c; mm):

$$\mathrm{Q} = \mathrm{R} \cdot \exp\left(\frac{-R_C}{R_0}\right) \qquad (6)$$

Table 1. Land use and predicted soil loss by sheet and rill erosion (t ha^{-1} yr^{-1}) in 1956 and 2004 for the Higuerón and Melgarejo catchments

Higuerón catchment	1956				2004			
Land use	Area		Soil loss		Area		Soil loss	
	ha	%*	mean	%*	ha	%*	mean	%*
Scrubland	49.9	30.2	3.8	5.9	55.0	33.2	4.1	6.1
Orchard (almond & olive)	15.4	9.3	66.2	31.3	36.5	22.0	54.4	54.0
Grazing land	7.2	4.4	62.5	13.8	7.2	4.3	51.5	10.1
Grazing land + scrubland	–	–	–	–	0.3	0.2	4.4	4.1
Grazing land + evergreen oak	49.6	30.0	4.3	6.5	35.0	21.1	87.4	0.6
Scrubland + evergreen oak	3.7	2.2	3.7	0.4	12.0	7.2	3.8	1.2
Rural road	0.7	0.4	54.1	1.1	3.5	2.1	67.7	6.5
Abandoned orchard	33.1	20.0	34.2	34.6	14.2	8.6	39.7	15.4
Settlement	0.1	0.1	–	–	0.4	0.2	–	–
Vineyard	5.7	3.5	35.6	6.3	1.1	0.6	39.7	15.4
Orchard terrace	–	–	–	–	0.5	0.3	17.2	0.2
Total catchment	165.5	–	19.7	–	165.5	–	22.3	–

Melgarejo catchment	1956				2004			
Land use	Area		Soil loss		Area		Soil loss	
	ha	%*	mean	%*	ha	%*	mean	%*
Scrubland	12.5	8.4	1.4	1.4	–	–	–	–
Orchard (almond & olive)	13.7	9.2	46.3	51.2	–	–	–	–
Grazing land	5.4	3.6	55.5	24.2	–	–	–	–
Scrubland + evergreen oak	7.4	5.0	2.9	1.7	–	–	–	–
Rural road	1.2	0.8	58.3	5.5	7.9	5.3	37.0	56.5
Abandoned orchard	1.6	1.1	7.2	0.9	–	–	–	–
Settlement	–	–	–	–	<0.1	<0.1	–	–
Pine forest	87.3	58.9	1.6	11.7	133.2	89.8	1.7	43.7
Scrubland + pine forest	19.2	13.0	1.8	2.8	7.2	4.9	2.3	3.2
Total catchment	148.3	–	8.3	–	148.3	–	3.5	–

*Percentage from the total surface and total soil erosion of the catchment

A correction was made to the different maps of effective runoff for the ephemeral streams because erosion by overland flow stops as soon as the overland flow reaches the stream. To account for this effect the estimated volume of runoff at the beginning of the gully channels is considered as the maximum runoff volume and a threshold value is estimated and used to calculate the cumulative runoff with a combined flow accumulation algorithm. This algorithm routes the overland flow downwards from the divides till the head of the gullies by using a multiple flow (MD) approach and by using a simple flow (D8) approach from the area of gully initiation till the outlet. For more details about the inputs and equations of the RMMF model and its modifications see Morgan (2001) and López-Vicente & Navas (2009b). All maps and the mathematical operations were done with the *ArcView GIS 3.2*® and *ArcGIS 9.3*® applications at 10 × 10 m of cell size.

Results and discussion

Both catchments suffered a reduction in the number of gullies (1st-order channels) from 1956 to 2004 because of the reforestation and/or the increment of vegetal cover and modification of the topography with farmer machinery. In 1956, ME and HI catchments presented 70 and 144 1st-order channels, respectively, mainly located in cultivated and abandoned orchards. However, in 2004 the number of these channels decreased by 59 and 74% in ME and HI, respectively. The drainage network order decreased from 5th to 3rd in HI, though 5th-order channels remain in ME despite of the significant reduction in the total number of gullies.

The maximum length of the drainage network and the drainage density also diminished: from 20.7 to 13.1 km and from 12.4 to 7.9 km km^{-2} in HI, and from 13.5 to 5.5 km and from 9.1 to 3.7 km km^{-2} in ME. Consequently, runoff flow is more concentrated in the 2004 scenario in fewer gullies and channels. This process could trigger more intense channel incision in the drainage network in both catchments and is expected to be more active in ME where a high vegetation cover leads to a dominance of subsurface flow processes. In agreement with this hypothesis frequent mass movements are described in the ME catchment confirming the presence of water flow within the soil profile. Further research will consider water consumption of the forested areas of the catchments by improving the assessment of potential and actual evapotranspiration. These factors are included in the estimation of the R_c factor (Eq. (6)).

Predicted values of overland flow per raster cell (Q_i) decreased 4% in HI and increased 2% in ME between 1956 and 2004, whereas values of effective

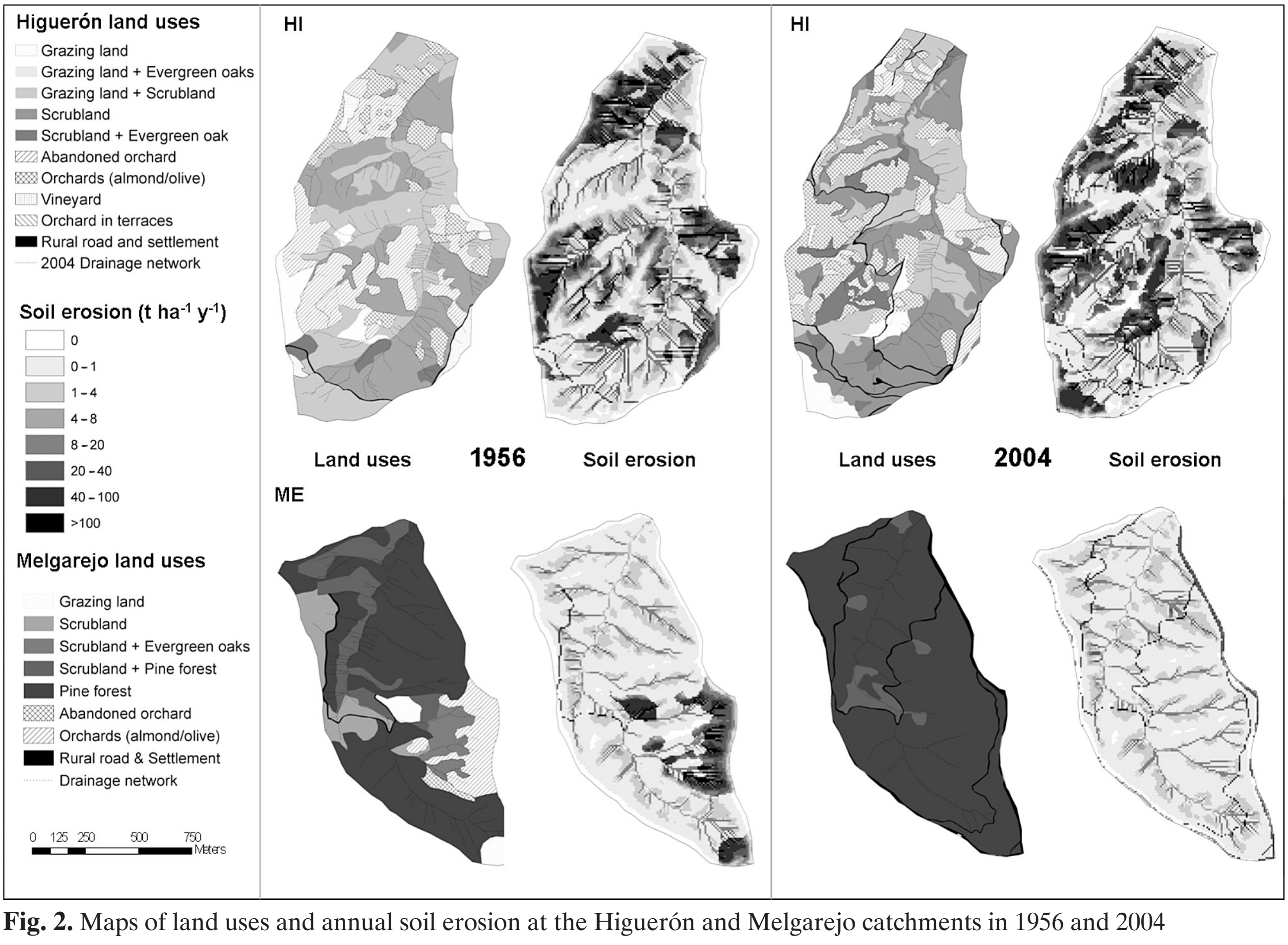

Fig. 2. Maps of land uses and annual soil erosion at the Higuerón and Melgarejo catchments in 1956 and 2004

cumulative runoff (CQ_{eff}) decreased 2 and 3% in HI and ME, respectively. The annual runoff coefficient (R_c) decreased from 39 to 37% in HI and increased from 24 to 25% in ME between 1956 and 2004. These results agree with the field observations of shortening gully length in both catchments. The different evolution between the values of Q, R_c and CQ_{eff} is explained by the role of the infiltration processes within the modified RMMF model and the spatial distribution of the main source areas of overland flow within the catchments. In this study we have used the same values of annual precipitation for the 1956 and 2004 scenarios and also of the threshold values for the assessment of CQ_{eff}. These assumptions have been made to facilitate the comparison of the predicted values for the different scenarios. The average threshold value calculated at the head of the gullies in HI and ME in 1956 were 2502 and 1968 mm yr^{-1}, respectively.

In the 1950s conditions, the type and distribution of land uses mainly favoured sheet wash and the rapid concentration of surface flow in gullies due to the topography, resulting in more intense erosion processes, especially significant in HI where the mean erosion rate increased 13% in 2004 reflecting the expansion of cultivated land (137% increment of the area with orchards). However, soil erosion decreased by 58% in ME in accordance with the good vegetation recovery of the abandoned fields by pine forest (Table 1). The highest rates of erosion appeared in those areas where the ground cover and canopy cover factors had their lowest values such as in the grazing + evergreen oak land use in HI-2004 (87 t ha^{-1} yr^{-1}), where overgrazing has created almost bare soil conditions. Scrublands and pine forest produced low values of soil loss (less than 5 t ha^{-1} yr^{-1}) whereas high rates were obtained in roads in the two catchments and in 1956 and 2004 (mean values between 37 and 68 t ha^{-1} yr^{-1}).

Between 1956 and 2004, the mean erosion rate in the intergully areas decreased from 29.7 to 28.1 t ha^{-1} yr^{-1} (5%) and from 11.6 to 5.0 t ha^{-1} yr^{-1} (57%) in HI and ME, respectively. These results are in agreement with the fall of the predicted total volume of cumulative runoff and validated with direct field observations. In 2004 the expansion of the vegetation cover in both catchments (increment of almond orchards and decrease of grazing land and vineyards in HI and huge increment of pine forest in ME (90% of the total surface in 2004)) leads to an increase of the water infiltration conditions. The mean and median values of the contributing upslope area at the head of the gullies increased in both catchments from 0.07 to 0.12 ha and from 0.08 to 0.54 ha (median values), for HI and ME, respectively. The mean and median values of slope steepness at the initiation point of the gullies remained similar for the two catchments and years. These results indicate a clear change in the erosive dynamic of the gully systems, from a more erosive-prone situation to a more stable and depositional-prone scenario.

Nevertheless, in this study we have not considered the so-called “effect of clear water” erosion process. Although less volume of cumulative runoff is expected in 2004 within the gully systems, the runoff erosivity in the active gullies can be higher due to a drop in sediment concentration. Nyssen et al. (2008) observed this process in semi-arid rangelands in Ethiopia where an increment of vegetal cover on hillslopes reduced interrill and rill erosion on the hillslopes but enhanced gully erosion in concavities. This process may be emphasized by the fact that the gully network in HI and ME is shorter in 2004 than in 1956. Hence, further improvements in the modified RMMF model will include the clear water effect and the increment of the runoff transport capacity as a result of the decreased sediment load delivered from the hillslopes to the gullies. Moreover, it is likely that the mean erosion rate estimated by the model in terraced orchards could be overestimated because these fields present a medium-steep topography that is not reflected in the DEM.

Results of this study underline the complexity of the evolution of soil erosion processes in gullied catchments as an increase in vegetation cover promotes a decrease in both the average soil erosion rates and extension of the gully network such as in ME although a decrease in the gully network can occur at the same time as average values of soil erosion increase mirroring the increment of the cultivated area (HI catchment).

Conclusions

The application of the modified RMMF model allows the spatial identification of the main erosion-prone areas in the Melgarejo and Higuerón catchments in 1956 and 2004.

The model seems to be sensitive to the parameters of soil and canopy cover, as well as to the value of effective cumulative runoff. The decrease in predicted volumes of effective runoff within the gullies in 2004, in relation to the estimated values in 1956, and the consequent lower rates of soil loss (by sheet and rill erosion) are in agreement with field observations of vegetation recovery in the upper part of the gullies and the decrease in their total length. The different land use changes occurring in HI and ME explain the different rates of spatially distributed soil erosion. Results of this study underline the complexity of soil erosion dynamic in gullied Mediterranean catchments where a general increase in soil erosion due to land use changes can occur simultaneously with a decrease in erosion rates within the gully system.

This study proves the usefulness of the modified RMMF model to simulate the effect of land use changes on overland flow and soil erosion and its further application will be of interest to assess the effect of future land use scenarios at catchment scale.

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