HYDROLOGICAL AND EROSION PROCESSES IN TERRACED FIELDS: OBSERVATIONS FROM A HUMID MEDITERRANEAN REGION IN NORTHERN PORTUGAL

Short title: HYDROLOGY AND EROSION IN A HUMID MEDITERRANEAN TERRACED FIELD

João Pedro Nunes*[1], Léonard Bernard-Jannin[1, 2], María Luz Rodríguez Blanco[3], Juliana Marisa Santos[1, 4], Celeste de Oliveira Alves Coelho[1], Jan Jacob Keizer[1]

1) CESAM & Dept. Environment and Planning, University of Aveiro, Portugal
2) École Nationale Supérieure Agronomique de Toulouse, Institut National Polytechnique de Toulouse, France;
3) Faculty of Sciences, University of A Coruña, Spain;
4) Institute of Geography, Friedrich-Schiller-Universität Jena, Germany.

***Corresponding author:** João Pedro Nunes

E-mail: jpcn@ua.pt

Address:
Dept. Environment and Planning, University of Aveiro
Campus Universitário de Santiago
3810-193 Aveiro
Portugal

Phone: (+351) 234 370200 (ext. 22636)

Keywords: hydrological processes; erosion; Mediterranean climate; terrace; águas de lima

This is the peer reviewed version of the following article:

Nunes J.P., Bernard-Jannin L., Rodríguez Blanco M.L., Santos J.M., Coelho C.O.A., Keizer J.J. 2018. Hydrological and erosion processes in terraced fields: observations from a humid Mediterranean region in northern Portugal. Land Degradation and Development 29 (3): 596-606 (DOI: 10.1002/ldr.2550).

Abstract

Terraces are a common Mediterranean feature influencing soils, slopes and subsurface hydrology; however, little is known about their impact on hydrological processes, especially in humid regions. This work studied hydrological and erosion processes in the "águas de lima" terrace system common in northwestern Iberia, characterized by wet season irrigation to keep soils saturated and avoid frost on winter pastures. Soil moisture, vegetation height, runoff and sediment yield were monitored for a terraced field in northern Portugal during 19 months. Relationships between rainfall, soil, vegetation, runoff and erosion were analyzed for 49 rainfall events, and within-storm patterns of soil moisture and runoff were further evaluated for the 12 largest events. Monitoring included two wet seasons with 1264 and 951 mm rainfall. Runoff followed rainfall with 20.5 and 3.8 mm, and was mostly related with event and pre-event rainfall. Combined with hydrograph analysis, this indicated a dominance of saturation-excess runoff generation, probably related with the presence of a shallow water table caused by limited drainage and constant irrigation during winter. Rill erosion was only observed as a result of run-on from the irrigation network. Sediment yield was low, 0.01 and 0.02 Mg ha^{-1} in the first and second year, and related with runoff; but vegetation cover was found to limit sediment concentration. This work indicates that "águas de lima" terraces promote saturation, runoff generation and a small amount of sediment yield which does not appear relevant for soil conservation. Further work is needed to better understand and conceptualize these processes.

Keywords: hydrological processes; erosion; Mediterranean climate; terrace; águas de lima

Introduction

Terraces are a common feature of agricultural landscapes throughout the world, built to conserve soil and retain moisture in areas otherwise subject to erosion after millennia of agriculture and grazing (Hooke, 2006; Li et al., 2014). In the Mediterranean, terraces have been an integral part of the landscape since before Roman times (Blondel, 2006); however, land abandonment in recent decades (Alonso-Sarría et al., 2015; Cerdà, 1997) has led to poor terrace maintenance, promoting their collapse and increasing erosion rates (García-Ruiz and Lana-Renault, 2011), which has led to a recent research focus on hydrological and erosion processes in terraced fields.

Recent reviews for the Mediterranean (Maetens et al., 2012; Stanchi et al., 2012) have found a greater research focus on the impacts of terrace abandonment and on the dryer regions. However, terraces are also present in humid Mediterranean and sub-Mediterranean climates, used to support pasture in mountain regions (Stanchi et al., 2012), which have received little attention. One of the few studies in the sub-Mediterranean Pyrenees (Gallart et al., 1994; Llorens et al., 1997) has shown a more complex picture for soil conservation than in drier areas; while these terraces promoted soil saturation and additional overland flow generation, potential increases in erosion were counteracted by permanent vegetation cover and the terrace walls themselves.

An important terraced landscape is found in the mountains of the humid Mediterranean and sub-Mediterranean region of the northwestern Iberian Peninsula, representative of other humid climate terraces. This terracing system is part of a surplus irrigation system called "águas de lima" which was described by Ribeiro (1945), consisting of a network of irrigation channels linking terraced pasture fields; despite the humid climate, irrigation is needed to keep pasture fields saturated in winter and prevent frost damage. Recently this system has also been used to irrigate maize and other vegetables during the dryer summer season. Fields are often bounded both by terraces and permanent cultures, mostly fruit trees or vineyards.

Pereira et al. (2007) proposed a runoff generation process for "águas de lima" similar to the one observed by Gallart et al. (1994) and Llorens et al. (1997), caused by terrace-promoted soil saturation and saturation-excess runoff generation; however, they did not consider impacts for soil erosion. This region has recently experienced large-scale afforestation which has been considered as a soil conservation measure on steep slopes; however, the recurrent fires associated with these forests lead to strong erosion in the aftermath (Shakesby, 2011), especially after post-fire replanting measures (Martins et al., 2013). It is difficult to assess the role of afforestation for soil protection without information about erosion in traditional terraced fields.

This work addresses this issue for a terraced field in an "águas de lima" system, located in a humid Mediterranean catchment in north-central Portugal. Soil properties inside the field were described, and vegetation growth, meteorology, soil water, runoff, erosion and sediment yield were regularly monitored during 19 months. The results were used to assess the processes behind runoff generation and sediment yield.

Materials and methods

Study area

This work was developed in an experimental field in the municipality of Macieira de Alcôba, located at an altitude of 470 m a.s.l. on the Caramulo mountain range in north-central Portugal. The local climate is humid Mediterranean. Average annual rainfall at the nearby Pousadas meteorological station for 2002-2012 was 1294 mm, varying between 818 and 1667 mm. 72% of rainfall is concentrated during a cold wet season lasting from October to March (average temperature 10.8 ºC), followed by a warm dry season (average temperature 17.6 ºC). The field and the agricultural surroundings overlay granitic bedrock. Ferreira (1997) provides a detailed overview of the area.

The experimental field is shown in Figure 1 and Figure 2. It has a surface area of 1875 m^2 and an average slope gradient of 8.6 %. The lower (western) part is flat and ends in a terrace wall made of mortared stone and reaching the bedrock, which also bounds the northern side. The terrace wall creates a topographic discontinuity of c. 1 m with the fields downslope. Olive trees are planted along these walls. The field is hydrologically connected with an "águas de lima" irrigation channel network, connecting the terraced fields surrounding the Macieira de Alcôba village; an example of these systems and their management is described by Salesse (2003). The network links the natural springs and irrigation tanks in the village upslope, with the main channel downslope, through open channels made of stone slabs near the terraces and of concrete near the village. Run-on from this network occurs at a single point shown in Figure 1.

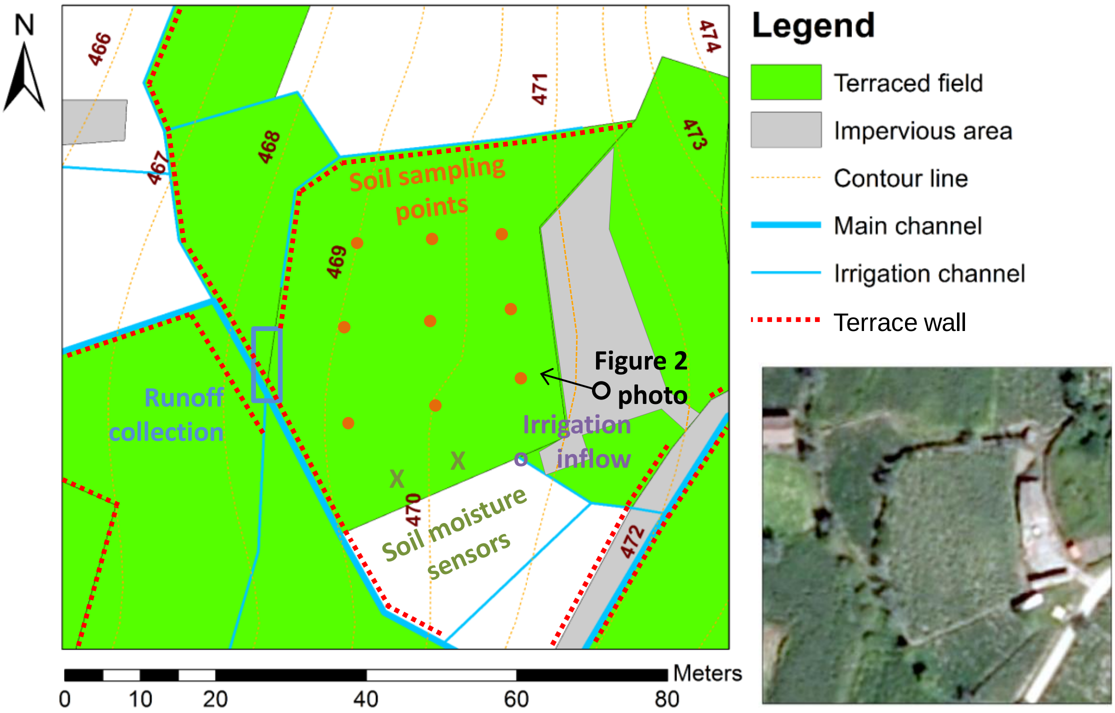

Figure 1. Experimental terraced field with location of monitoring points (left) and respective aerial photograph (right).

Top: October 2010; bottom: March 2011

Figure 2. View of the experimental field, from the highest point facing downslope; it was taken from the southeastern corner facing northwest (see Figure 1). The upper picture was taken in October 2010, as pasture was just beginning to grow, while the lower picture was taken in March 2011.

Throughout the study period, the field presented an annual crop rotation between wet season pasture and dry season maize. In September/October, the field is plowed and pasture is sown; the field is constantly irrigated and kept saturated to avoid frost. Figure 2 shows the contrast between soil cover in the early and late stages of pasture growth. Pasture is harvested in May for silage, and the field is again plowed and maize is sown. Maize is periodically irrigated as well, and harvested in September/October. A similar rotation system is present in most terraces of the network.

Most of the irrigation water comes from natural springs located on the granitic bedrock near the Macieira de Alcôba village, fed by rainwater percolating from uphill forests, which show a strong seasonal behavior. This source is supplemented by rainfall collection tanks in the wet season, and from water pumped from impoundments in the local streams in the dry season. The combination of abundant rainfall and a relatively impervious bedrock leads to an abundant irrigation water supply in most years. The irrigation network is jointly maintained and regulated by the farmers, with the help of the local government. Irrigation regulation broadly follows the system described by Salesse (2003), with no regulation during the wet season (pasture) when water supplies are abundant, and regulation of amounts and timings during the dry season (maize) when supplies are lower.

Field characterization

The field was characterized by a survey in 01/03/2011. Soil depth, shear strength and compaction was measured in nine points evenly distributed over the field (Figure 1), using respectively a soil probe (buried until bedrock was found), a torvane and a penetrometer, taking 5 measurements per point for the latter 2. Soil probe samples along depth were used to classify the soil based on soil color and texture. Surface roughness was measured using a pin profiler and was used to calculate surface detention storage following Kamphorst et al. (2000). For a subset of the points, measurements were also made of topsoil bulk density (6 points, 3 samples per point), topsoil and subsoil texture (4 points, with samples taken between 0 and 20 cm, and between 20 cm and maximum soil depth), and surface (near-)saturated hydraulic conductivity (K_{sat}) using the mini-disk infiltrometer (5 points, 3 tests per point). A snapshot of soil moisture spatial patterns was taken by sampling a subset (6 points, 3 samples per point). Finally, a sample was taken for laboratorial determination of the soil water retention curve at pF 1.8, 2.0, 2.54 and 4.2. All these parameters, except soil water retention, were also measured at seven points in other nearby terraces between 9 and 11/05/2011, to assess if soils in this field were representative of the system.

Continuous monitoring

The field was monitored between 8 November 2010 and 31 May 2012, during almost two hydrological years (starting with the wet season in October and lasting until the end of the following dry season in September). Rainfall was recorded at 15 min intervals with an automatic rain gauge, and data quality assessed using a rainfall totalizer measured every 1 to 2 weeks.

Runoff was collected downslope at the lowest point of the terrace wall, which was reinforced with metal plates to ensure the bounding of surface runoff (Figure 1 and Figure 2). Runoff during individual events was measured using two tipping-bucket devices; it was then collected in tanks, with volumes measured each 1 to 2 weeks to validate the tipping-buckets. 100 mL samples of collected runoff were used to determine sediment concentrations in the laboratory, by the gravimetric method using 0.45 µm filters oven-dried at 105ºC during 24 hr (APHA, 1998).

Soil moisture content was recorded at 15 min intervals at four locations along the field's southern side (Figure 1 and Figure 2), using four pairs of EC-5 sensors (Decagon Devices) installed at 2.5 and 7.5 cm depth; the average of these points was used in the analysis. The occurrence of run-on from the irrigation network from the southeast (Figure 1) was also evaluated at 1- to 2-weekly intervals from hydrological evidence, especially the movement of debris in the channel; the amount of run-on was not measured as it was not possible to instrument the irrigation channel. Erosion within the field was characterized by identifying and measuring the volume of rills, using the closest bulk density measurement to estimate the mass of soil loss. Finally, pasture vegetation height was measured at 1 to 2 weekly intervals.

Plowing operations interrupted measurements on several occasions. Runoff collection was interrupted between May and September 2011 during maize cultivation; however, no important rainfall events occurred in this period. Soil moisture sensors were also removed in May 2011, re-installed in June, removed again in September and re-installed in October. Unexpected mid-winter plowing in January 2012 destroyed part of the sensors; the others were installed in a nearby permanent pasture plot.

Event-based data analysis

Relationships between rainfall, runoff and sediment yield were studied by analyzing 51 rainfall-runoff events with more than 10 mm rainfall, separated by intervals greater than 3 hours. Since sediment export was only measured at the weekly scale, in weeks with more than one runoff event (9 out of 28), sediment concentration was assumed the same for all events; however, 8 of these weeks had a clearly dominant sediment-export event. The relationship between different variables was assessed using Pearson correlation coefficients and a significance level of 0.05. The assessed variables included:

- event rainfall characteristics: total rainfall, maximum 30-min intensity, mean intensity and duration;
- pre-event conditions: antecedent rainfall during 1, 3, 5, 7, 15 and 21 days before the event, initial soil moisture and vegetation height (for pasture);
- runoff and sediment yield: total runoff and runoff/rainfall coefficient, sediment yield and concentration in runoff.

12 events with rainfall above 40 mm and measured runoff were subjected to an in-depth hydrograph analysis, comparing continuous (15 min) measurements of soil moisture, rainfall, and runoff rates during the event.

Results and Discussion

Field characteristics

Table 1 shows the soil properties of the terraced field, classified as a humic Cambisol (IUSS Working Group WRB, 2014). Measured soil field capacity (pF 2) and wilting point (pF 4.2) were respectively 38.7 and 23.4% (v/v);the soil water retention curve derived from these parameters (van Genuchten, 1980) led to an estimation of saturated and residual water contents of respectively 59.2 and 21.7% (v/v). Organic matter content showed a notable decrease with depth, between topsoil and subsoil. Soil texture was between loam and sandy loam, with little variation with space or depth; the soil also showed an important presence of coarse fragments, again without spatial or depth patterns. These coarse soils are typical of those usually found in terraces (Stanchi et al., 2012). Soil depth was noticeably shallower in the west and northwestern points (40-50 cm) than elsewhere (75-110 cm).

Table 1. Variables evaluated in the characterization of terraced fields in the study area.

	Study terraced field				**Other terraced fields**			
	Minimum	**Maximum**	**Average**	**C.V. (%)^a**	**Minimum**	**Maximum**	**Average**	**C.V. (%)^a**
Physical properties								
Soil depth (cm)	40.0	110.0	72.8	31.9	35.0	120.0	84.3	37.9
Shear strength (kg cm^{-2})	2.0	4.0	2.9	78.7	1.2	2.7	2.0	30.8
Compaction (kg cm^{-2})	0.3	1.5	0.8	41.4	0.2	1.7	0.9	74.1
Bulk density (kg cm^{-3})	0.9	1.3	1.1	9.0	0.9	1.1	1.0	8.9
Surface storage capacity (mm)	2.4	5.0	3.6	23.0	2.8	4.9	4.1	22.6
Saturated hydraulic conductivity (mm h^{-1})	11.4	75.7	31.2	64.9	13.5	94.5	43.6	79.2
Texture USDA - topsoil (0-20 cm)								
Coarse fragments (soil fraction)	0.16	0.31	0.24	26.6	0.12	0.24	0.16	32.7
Organic matter (soil fraction)	0.10	0.15	0.13	16.1	0.07	0.13	0.10	24.5
Sand (fines fraction)	0.47	0.60	0.55	11.0	0.37	0.69	0.46	34.5
Silt (fines fraction)	0.27	0.35	0.30	11.4	0.20	0.46	0.39	32.5
Clay (fines fraction)	0.12	0.18	0.15	18.3	0.11	0.18	0.16	20.1
Texture USDA - subsoil (> 20 cm)								
Coarse fragments (soil fraction)	0.19	0.40	0.27	35.3	0.24	0.25	0.25	2.9
Organic matter (soil fraction)	0.05	0.09	0.07	23.1	0.05	0.08	0.07	32.6
Sand (fines fraction)	0.45	0.66	0.57	15.5	0.44	0.75	0.60	36.8
Silt (fines fraction)	0.25	0.45	0.32	27.9	0.17	0.39	0.28	55.6
Clay (fines fraction)	0.09	0.14	0.11	19.7	0.08	0.16	0.12	47.1
a: C.V. is the coefficient of variation, i.e. the standard deviation divided by the average								

Shear strength and compaction were normal for agricultural fields and followed an increasing north-south gradient. Surface storage capacity increased from the bottom to the top of the slope, with values typical of an unplowed field (Kamphorst et al., 2000). Saturated hydraulic conductivity (K_{sat}) was relatively high and followed a strong decreasing northeast to southwest gradient; topsoil bulk density and soil moisture (which was close to saturation in the survey day, between 33.3 and 44.4%) showed a very similar behavior to K_{sat}.

Table 1 also shows that the properties of soils in the selected field fell inside the range of those found elsewhere in the terraced system, although topsoil tended to be coarser than elsewhere. This indicates that the selected field was representative of other terraced fields in the Macieira de Alcôba system.

Overall runoff and sediment yield

Figure 3a shows daily rainfall, runoff and sediment yield for the study field. There was a strong contrast between hydrological year 2010/2011, with an average amount of rainfall (1264 vs. 1294 mm average), and 2011/2012 which had a very dry winter (79 vs. 401 mm average) but a relatively wet spring (363 vs. 250 mm average). This contrast was also reflected in runoff amounts of 20.5 mm in the first year (concentrated in late autumn and winter) and 3.8 mm in the second (concentrated in autumn and spring). In contrast, soil moisture (Figure 3b) showed similar patterns in both years, exceeding field capacity during the wet season (40 to 60%), even in the second year.

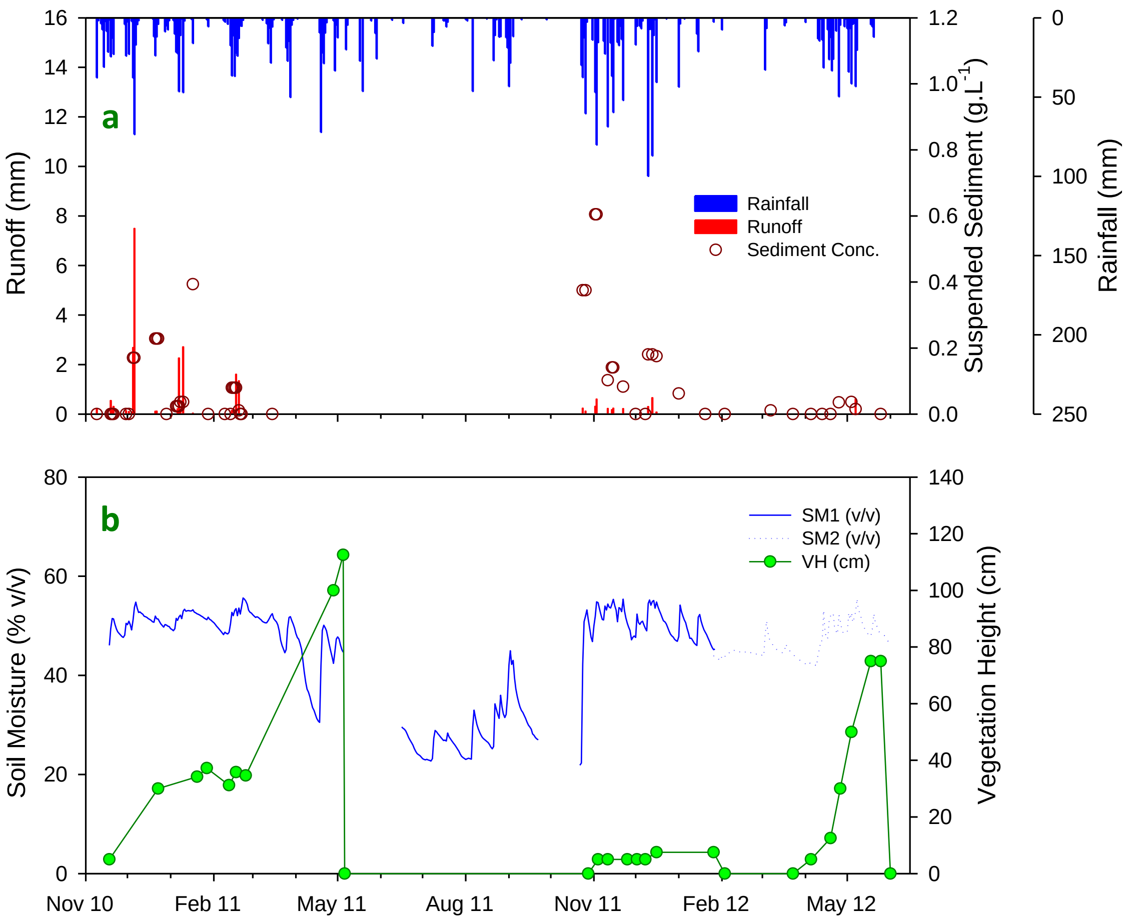

Figure 3. a) daily rainfall, runoff and sediment concentration from the field. b) soil moisture (SM1: measured inside the field, SM2: measured in a nearby pasture) and height of pasture vegetation (VH); the field was covered by maize between May and November 2011, but vegetation height was not recorded.

Suspended sediment concentration followed the same seasonal pattern as runoff, but with an added tendency for low values in spring at the period of maximum vegetation growth. Sediment yields were respectively 0.02 and 0.01 Mg ha^{-1} in the first and second year, indicating negligible erosion rates. During the first year, rills developed which roughly linked the inflow of the irrigation channel with the lower part of the slope (Figure 2). The rills were fully developed by December 2010 and remained unchanged until being plowed over in April 2011. Rill erosion was estimated at 0.66 Mg ha^{-1}, i.e. one order of magnitude above exported sediment during the first year and pointing to important deposition near the edge of the terrace, a fact which was confirmed with field observation.

Event analysis

49 rainfall-runoff events occurred during the measurement period, mostly (73%) during the wet season. Table 2 characterizes the variables used in the event analysis, and Table 3 shows the correlation coefficients of surface runoff and sediment yield of the individual events with rainfall and field-related variables.

Table 2: Summary of the variables evaluated for the rainfall-runoff events during the study period.

		Minimum	Maximum	Average	C.V. (%)^a
Rainfall					
P	Total event rainfall (mm)	10.1	74.7	28.7	57.4
IP30	Maximum 30-min rainfall intensity (mm h^{-1})	3.2	28.7	11.1	52.7
IP	Mean rainfall intensity (mm h^{-1})	0.7	6.2	2.3	55.2
Pd	Rainfall duration (h)	2.5	64.3	16.1	70.8
Pre-event conditions					
AP1	Rainfall 1 day before the event (mm)	0.0	76.8	9.8	150.1
AP3	Rainfall 3 days before the event (mm)	0.0	129.1	25.7	105.9
AP5	Rainfall 5 days before the event (mm)	0.0	151.9	35.6	98.0
AP7	Rainfall 7 days before the event (mm)	0.0	178.6	47.2	90.3
AP15	Rainfall 15 days before the event (mm)	0.0	299.0	115.3	69.3
AP21	Rainfall 21 days before the event (mm)	0.0	369.9	132.3	68.8
SM	Initial soil moisture at 0-10 cm depth (%)^b	22.9	54.8	47.9	12.8
VH	Pasture vegetation height (cm)^c	0	115.1	25.8	1.1
Runoff and soil loss					
R	Surface Runoff (mm)	0.0	7.5	0.5	2.6
RC	Runoff coefficient (%)	0.0	12.0	1.0	2.1
SY	Sediment yield (Mg ha^{-1})	0.0	0.017	0.001	3.1
SSC	Mean sediment concentration in runoff (g L^{-1})	0.0	0.6	0.1	1.4
a: C.V. is the coefficient of variation, i.e. the standard deviation divided by the average					
b: average of all values recorded by the soil moisture sensors at the start of the event					
c: estimated from the two closest measurements by linear interpolation					

Table 3: Pearson correlation coefficient matrix between the analyzed variables for plot runoff (n=49 for all variables except SM, where n=38). Correlation coefficient is significant at the 0.05 level for underlined numbers, and at the 0.01 level for bold and underlined numbers.

	P	IP30	IP	Pd	AP1	AP3	AP5	AP7	AP15	AP21	SM	VH	R	RC	SY	SSC
P	-															
IP30	**0.39**	-														
IP	-0.12	**0.42**	-													
Pd	**0.77**	-0.03	**-0.56**	-												
AP1	0.17	**0.32**	-0.20	0.25	-											
AP3	**0.33**	0.30	-0.16	0.29	**0.69**	-										
AP5	**0.48**	0.26	-0.18	**0.37**	**0.53**	**0.86**	-									
AP7	**0.46**	0.11	-0.20	**0.35**	**0.42**	**0.75**	**0.90**	-								
AP15	**0.37**	0.09	-0.01	0.18	0.14	**0.35**	**0.51**	**0.64**	-							
AP21	**0.36**	0.10	-0.04	0.17	0.09	0.30	**0.48**	**0.60**	**0.94**	-						
SM	0.19	0.06	0.06	0.13	0.24	0.38	**0.43**	**0.50**	**0.61**	**0.59**	-					
VH	0.06	0.16	-0.02	-0.03	0.01	0.11	0.08	0.06	0.07	0.12	**-0.44**	-				
R	**0.56**	**0.47**	0.18	**0.39**	**0.35**	**0.43**	**0.49**	**0.43**	0.22	0.27	0.16	-0.06	-			
RC	**0.51**	**0.48**	0.19	0.25	**0.40**	**0.50**	**0.54**	**0.47**	0.24	0.26	0.19	-0.10	**0.98**	-		
SY	**0.43**	**0.48**	-0.03	0.34	**0.36**	0.28	0.30	0.28	0.14	0.21	0.16	-0.12	**0.90**	**0.86**	-	
SSC	-0.06	0.11	-0.09	-0.02	0.19	0.02	-0.07	-0.03	0.00	-0.04	0.12	**-0.49**	0.04	0.11	0.25	-

Near-surface soil moisture (SM) was significantly correlated with all AP variables except AP1, and negatively related with vegetation height (VH), since that pasture growth extended into the dry season (Figure 3). Total runoff (R) and runoff coefficient (RC) were very strongly correlated between themselves, as well as with total rainfall (P), 30 min rainfall intensity (IP30) and antecedent precipitation between 1 and 7 days (AP1-7), especially AP5. R was also correlated with event duration (Pd). Runoff correlation with IP30 could suggest a contribution of infiltration-excess runoff (e.g. Boix-Fayos et al., 2005; Kirkby et al., 2005). However, average IP30 was below average K_{sat} (11.1 vs. 31.2 mm.h^{-1}); the lower K_{sat} at the western end of the plot could have led to the generation of infiltration-excess runoff there.

Runoff correlation with AP1-7 could indicate a contribution of saturation-excess runoff. A closer look at the data (Figure 4) revealed a non-linear relationship of runoff with rainfall and AP5. Little to no runoff was observed for events with up to 40 mm rainfall, while beyond this threshold runoff increased with increasing P, especially for AP5>75 mm. Runoff was not significantly correlated with SM; however, this can be explained by the uniformly high SM values (usually above field capacity) throughout the rainy period (see Figure 2 and Table 2). Furthermore, the larger runoff volumes were mostly associated with the occurrence of run-on from the irrigation network (Figure 4); the accumulated antecedent rainfall could have increased discharge from springs and water held in tanks, leading to overflow during rainstorms.

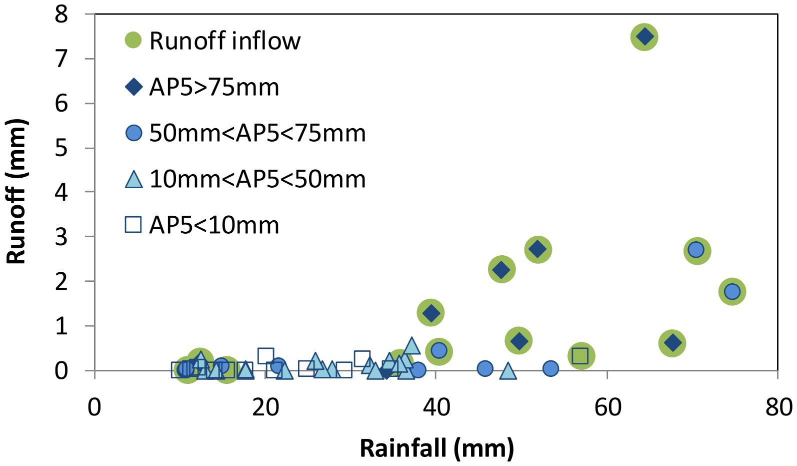

Figure 4: Relationship between event rainfall (P) and runoff (R), according to antecedent precipitation in the previous 5 days (AP5) and the presence or absence of runoff inflow to the plot from the irrigation network.

Sediment yield (SY) was highly correlated with runoff (R and RC), and in consequence, with the same factors with which runoff was correlated. Suspended sediment concentration (SSC), however, only showed a significant relation with vegetation height (VH). Figure 3 suggests that VH imposed an upper limit to SSC; a more detailed analysis (Figure 5) confirmed this, and also revealed that the runoff - sediment yield relationship tended to decrease with increasing pasture height. In fact, events when pasture was under 30 cm corresponded to 89% of SY, but only 51%

of total events, 60% of P and 59% of R. The correlations between R and SY for each class of pasture height distinguished in Figure 5b were all significant ($p < 0.01$), with coefficients exceeding 0.80 and increasing with shorter VH. Rill formation also occurred during a period of relatively short pasture (~27 cm).

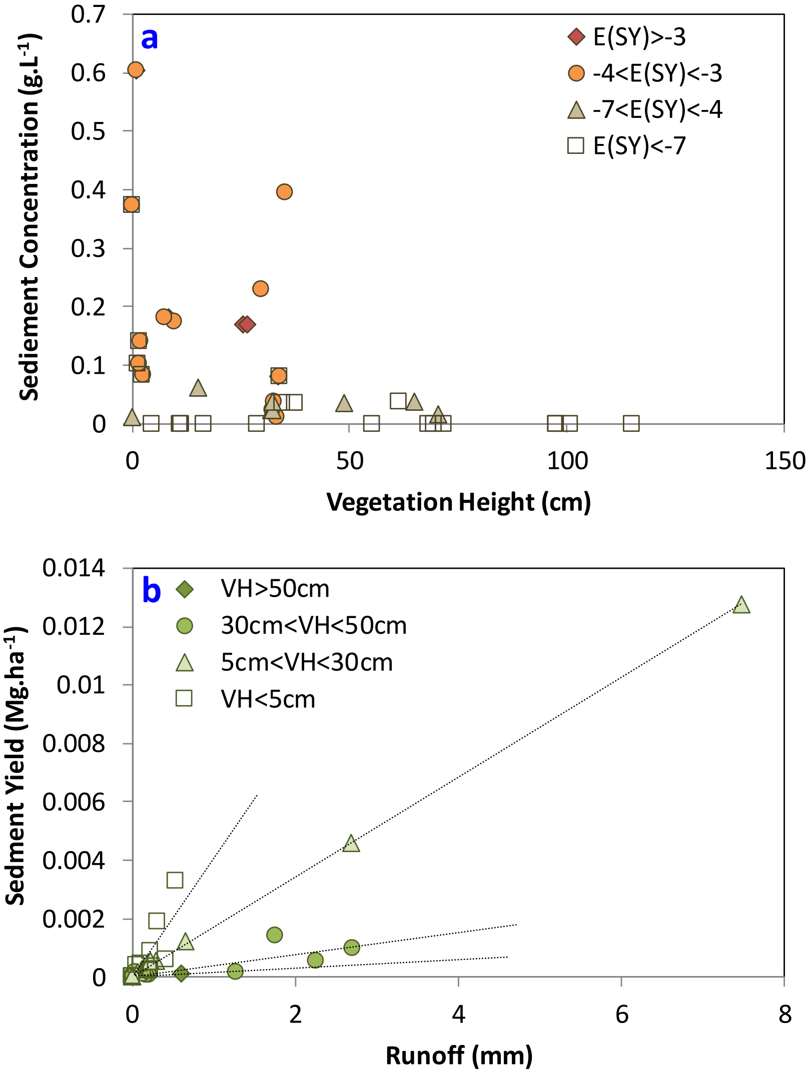

Figure 5: a) Relationship between vegetation height (VH) and plot sediment concentration (SSC) according to sediment yield (SY); the scale is given as the exponent for scientific notation, where E(-7) = $1x10^{-7}$ Mg.ha^{-1}, E(-4) = $1x10^{-4}$ Mg.ha^{-1}, and E(-3) = $1x10^{-3}$ Mg.ha^{-1}; in this scale, maximum observed SYpl is E(-2). b) relationship between plot runoff (R) and plot sediment yield (SY) according to the growth stage of pasture; dotted lines illustrate the linear regression for each group of observations.

Hydrograph analysis for major events

Twelve major events with more than 40 mm rainfall were selected for an in-depth hydrograph analysis. 9 occurred in the wet seasons of the first and second years and 3 at the start of the following dry season. Figure 6 and Figure 7 show respectively the instantaneous and accumulated rainfall and runoff for each event.

Runoff generation started at a consistent soil moisture threshold (Figure 6): 52-53% for events in late 2010 and early 2011, 50-51% for events in late 2011, and 54-55% for events in spring 2012. The difference in thresholds was probably due to the change in position of the soil moisture sensors described above. All thresholds suggested that part of the field reached saturation at the start of runoff generation (c. 59%). Saturation-excess runoff generation therefore appears to be the main mechanism during important rainfall events.

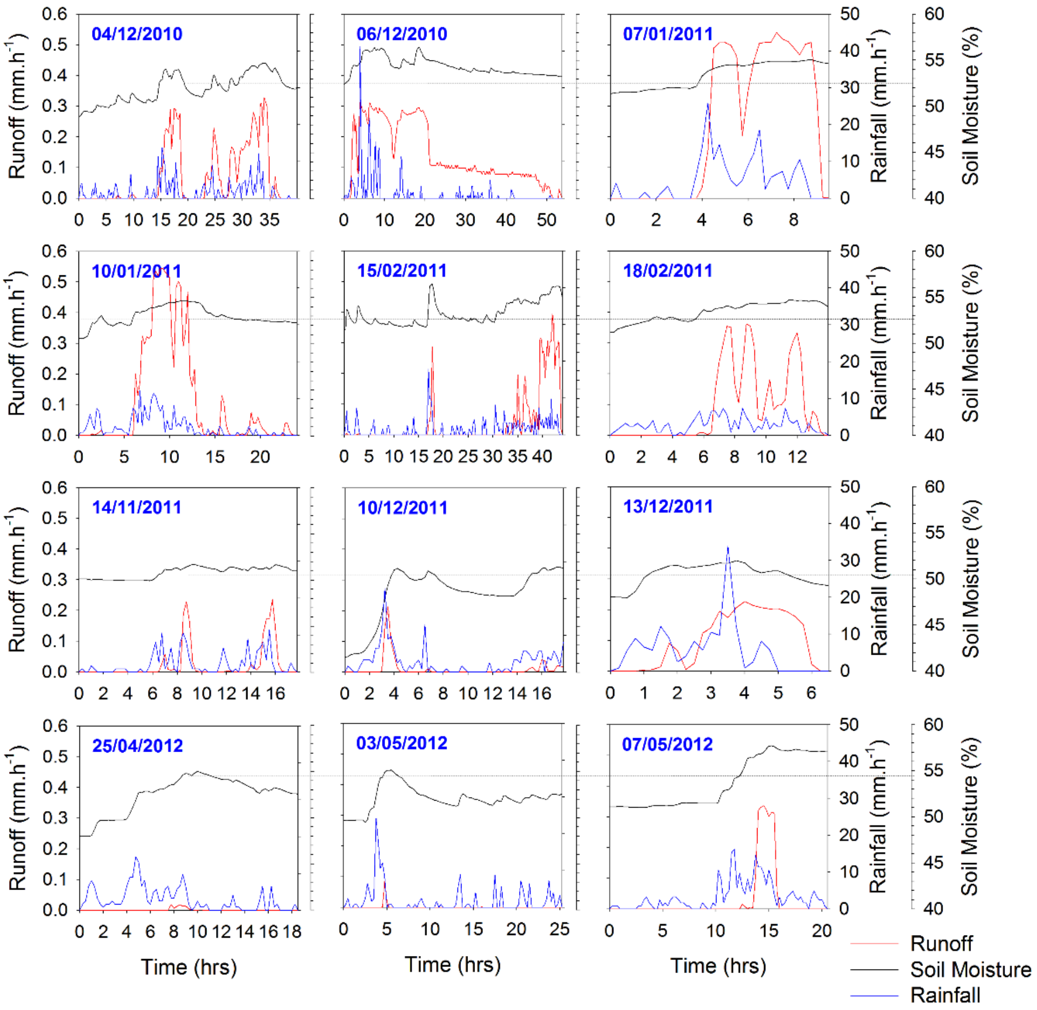

Figure 6. Evolution of rainfall intensity, runoff intensity and soil moisture (each 15 minutes) for 12 major rainfall/runoff events; the dashed lines represent the soil moisture threshold for the start of sustained runoff.

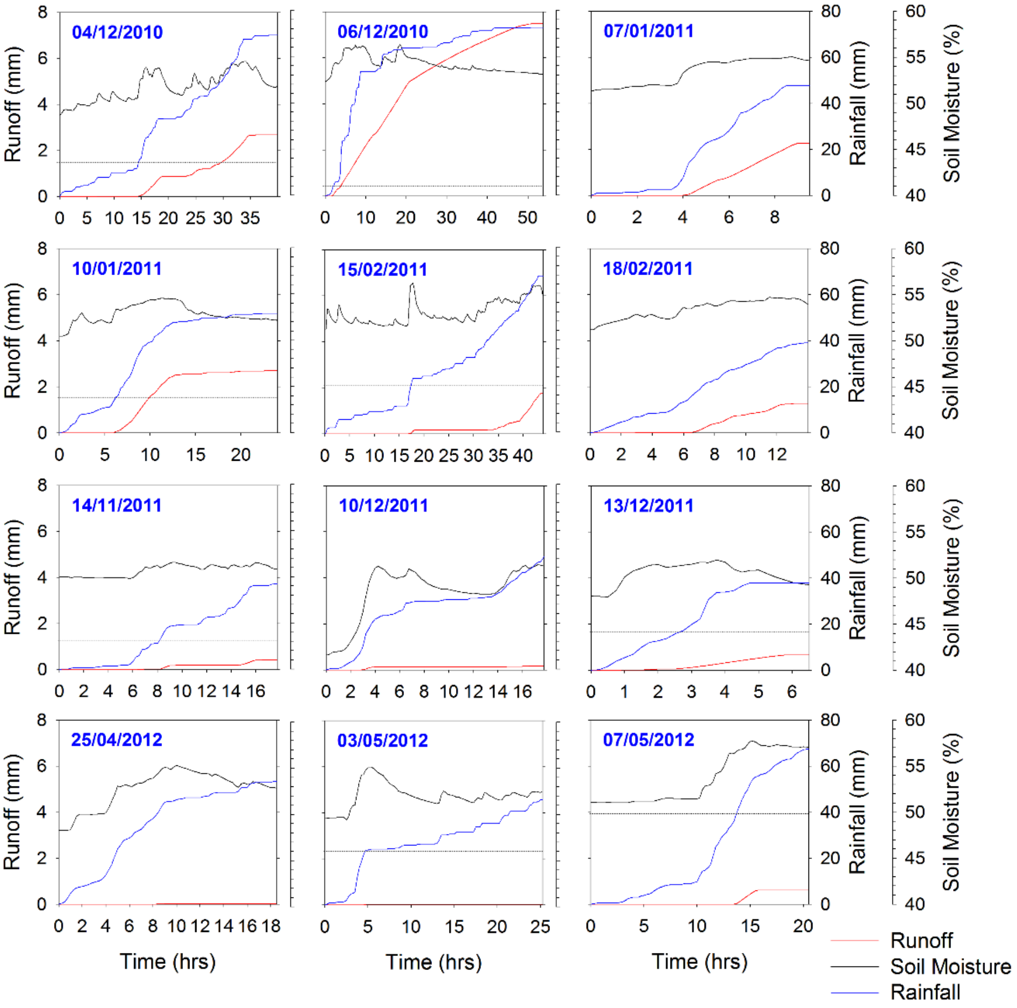

Figure 7. Evolution of cumulative rainfall, cumulative runoff and soil moisture (each 15 minutes) for 12 major rainfall/runoff events; the dashed lines represent the accumulated rainfall threshold for the start of sustained runoff.

The rainfall accumulation threshold for runoff initiation was notably more variable than that of soil moisture (Figure 7). Events occurring before the end of 2011, except 06/12/2010, presented a rainfall threshold between 10 and 20 mm, exceeding the field's 5 mm surface storage capacity (Table 1) and therefore suggesting infiltration before runoff initiation. However, events in the dry season of 2012 had a much higher rainfall threshold of around 20 to 40 mm, this despite soil moisture starting as high as in other events. Runoff accumulation patterns tended to follow closely cumulative rainfall accumulation patterns (Figure 7) except again for the 06/12/2010 event, again indicating saturation-excess runoff. Runoff coefficients after these thresholds were reached varied between events, indicating a significant role of other factors besides soil moisture and storm rainfall.

Figure 6 also suggests the occasional occurrence of infiltration-excess runoff generation. In 15/02/2011, 10/12/2011 and 03/05/2012, runoff started during 15-min rainfall peaks surpassing K_{sat} in at least the lowest part of the field (compare with Table 1) but stopped immediately afterwards. This process may also have occurred during the other storms, but the late occurrence of maximum intensities made it difficult to separate it from saturation-excess runoff.

The event of 06/12/2010 was exceptional in several aspects. First, initial soil moisture was close to the runoff initiation threshold; second, the event combined high total rainfall (64 mm), AP5 (97 mm) and IP30 (28.7 mm h^{-1}, approaching the field's average K_{sat}); and third, runoff continued at a constant and relatively high rate for quite some time after rainfall stopped (Figure 6 and Figure 7). The low cumulative rainfall for runoff initiation (4 mm) possibly corresponded to the surface storage capacity (Table 1). The continued runoff generation after rainfall stopped could be explained by run-on from the irrigation network, amounting to c. 34% of total runoff. This would also explain why rill formation was limited to this event, especially since the rill connected the irrigation network with the plot's outlet (Figure 2, top).

Hydrological processes

Soil moisture during the wet season was usually above field capacity, even during the dry winter of 2011/2012 (Figure 3), consistent with the winter irrigation employed in "águas de lima" systems. Evidence for run-on from the irrigation network was observed throughout the first wet season but not the second, as the severe drought constrained irrigation by the farmers.

The main runoff generation process was saturation-excess; infiltration-excess only appeared to be important for isolated events, as maximum rainfall intensities were generally below saturated hydraulic conductivity. This is consistent with data for cultivated fields in northern Spain (e.g. Giménez et al., 2012).

However, runoff generation depended more on antecedent rainfall (especially in the previous 5 days) than on initial soil moisture. Pereira et al. (2007) reported a similar dependence for other terraces in northern Portugal, and proposed a conceptual model for terraces overlaying granite bedrock, where saturation-excess runoff generation is linked with groundwater, through: (i) presence of a shallow water table resulting from a delay in drainage caused by the terrace wall; and (ii) groundwater resurfacing in downhill terraces, caused by pressure from this water table in uphill terraced fields.

A shallow water table could be present in the field at depths below those of the soil moisture measurements (i.e. below 10 cm). In fact, the terrace walls limiting the downslope part of the experimental field usually remained humid after rainstorms, possibly due to the water they retained. The strongest correlation with AP5 could then be related with the time required to drain the field after rainfall. A similar process has been observed by Gallart et al. (1994) and Latron and Gallart (2007) for humid sub-Mediterranean catchments, where the existing terrace network promoted saturation and saturation-excess runoff generation in upper and mid slopes. Terrace networks have been found to exert a strong impact on catchment hydrological connectivity elsewhere (Bracken et al., 2013). The shallow water table could have been created by winter irrigation, typical of this "águas de lima" system, in combination with antecedent rainfall. The winter drought of 2011/2012 limited available water for irrigation, possibly resulted in a lower shallow water table; this would explain why runoff generation in April and May 2012 involved higher rainfall thresholds than previous events (Figure 7).

As for groundwater re-surfacing, little evidence for this process was observed in this study, except for the decreasing soil moisture gradient with slope found at a single occasion. It is however possible that this process could be more important for terraced fields downhill from the study site.

The data also suggests an additional explanation for the importance of AP to add to those proposed by Pereira et al. (2007): run-on from the irrigation network. Since the "águas de lima" system requires an overflow of existing upslope reservoirs after rainfall accumulation (Salesse, 2003), it would be easier to activate during periods with high antecedent rainfall. Most of the 12 major storms revealed evidence for run-on from the irrigation network, except for the ones in April and May 2012 when the irrigation system was not used (Figure 7). Even so, only the storm of 06/12/2010 presented evidence for substantial run-on, suggesting that this process may only be important for infrequent events, and can therefore be thought of as a complementary process to the shallow water table.

Soil erosion and sediment yield processes

Rill erosion was only observed in the first year. The recorded rate of 0.66 Mg ha^{-1} was in the same order of magnitude as those reported for Mediterranean arable lands (0.5 to 5 Mg ha^{-1}; Cerdan et al., 2010; Hooke, 2006), but below the 15 Mg ha^{-1} observed by Rodríguez-Blanco et al. (2013) for a similar field in Galicia. The short duration of the monitoring period hampers a robust estimate of the average erosion rate for the study field. However, the link between this rill and the inflow from the irrigation network during the event of 06/12/2010 would classify it as infrequent and high-magnitude. Such extreme events typically increase sediment connectivity and drive erosion rates (Bracken et al., 2015). This could indicate an important link between the irrigation network and erosion. The nature of the irrigation channels would mean that run-on should not bring important quantities of sediment onto the field, but no observations were made to corroborate this.

Sediment export rates were, however, smaller than rill erosion by an order of magnitude. The export rate during the first year amounted to a sediment delivery ratio of 3% of the within-field erosion. This would indicate a high effectiveness of the terrace in trapping sediments eroded by the rill, c. 97%. Terraces usually trap 30 to 40% of within-terrace erosion but they become more effective for longer slopes such as the Macieira field, reaching levels similar to the ones observed (Maetens et al., 2012). In similar terraces within a sub-Mediterranean catchment in the Pyrenees, Llorens et al. (1997) observed a sediment yield of 1% of total erosion. Therefore, while the irrigation network could have been seen as promoting erosion in the first year, the terrace wall was able to contain most of it, with the trapping efficiency possibly increased by the presence of permanent vegetation near the field boundary. In the second year, sediment export would be due to interrill erosion; possibly, the lower parts of the slope (where ponding and surface runoff were observed) were the source areas of the exported sediments.

The seasonal variability of pasture cover (Figure 2) appeared to play a key role in the occurrence and timing of sediment losses. This can be attributed to the impact of vegetation density on rainfall interception and resistance to surface runoff, decreasing both splash detachment and sediment transport capacity by runoff (Govers, 1990; Morgan, 2005). In the first year, this prevented erosion after early stages of pasture development, i.e. after December (Figure 3). In the second year, however, the lack of irrigation for pasture severely limited vegetation growth, all but eliminating the vegetation cover effect until April. This explains why the strong decrease in runoff between the first and the second year (80%) led to a much smaller decrease in sediment yield (50%).

Comparison with afforested areas

Agricultural terraces in this region have been replaced by planted forests in recent decades, leading to terrace collapse due to lack of maintenance (Shakesby, 2011). While the results from this work indicate that this might have led to a decrease in saturation-excess overland flow, the soil water repellency typical of eucalypt and pine plantations (Santos et al., 2016) might have increased infiltration excess overland flow. In fact, terrace abandonment might help explain the observation made by Hawtree et al. (2015), who for the main river downstream from Macieira de Alcôba found that afforestation in the past century might have increased fast runoff generation; this possibility for large-scale impacts of terrace abandonment merits further research. As for erosion, mature forest stands typically have erosion rates of the same order of magnitude as those found in this study: c. 0.02 Mg ha^{-1} y^{-1} (Ferreira et al., 2008). However, to this should be added erosion rates after disturbances, such as forestry management operations such as rip-plowing, occurring once every 36 years for eucalypts and where erosion could reach as high as 50 Mg ha^{-1}; and after fires, which can reach between 1 and 10 Mg ha^{-1} in the first year (Ferreira et al., 2008; Shakesby, 2011). Finally, a recent forestry and post-fire management technique has been the construction of unsupported terraces for re-afforestation, where erosion can be as high as 36 Mg ha^{-1} in the months after construction (Martins et al., 2013). After a previous fire in Macieira de Alcôba, Ferreira (1997) measured similar erosion rates for two years: 2.2 and 0.02 Mg ha^{-1} y^{-1} in a post-fire and a grown plantation, respectively. This indicates that erosion in new forests could be of the same order of magnitude as that in terraces during most years, increasing by 2 to 3 orders of magnitude during infrequent but recurring disturbances, leading to an overall higher value.

Conclusions

The results of this study indicate that the terrace network promotes saturation-excess runoff generation, due to a combination between (i) wet season irrigation practices characteristic of the “águas de lima” system that aim at saturating soils to prevent frost damage to pasture; and (ii) the terrace wall limiting water drainage, leading to the occurrence of a shallow water table. In dry years with limited irrigation, results suggest a strong decrease of the runoff generation ratio. Direct run-on from the irrigation network was also found to occur, especially during the largest storms. Results also indicate that the terrace network promoted sediment export in consequence of additional runoff generation, but this was counteracted by the pasture cover made possible by terracing. Therefore, drought spells during winter may also have an erosion-promoting effect due to the lack of water to irrigate pasture and preventing its growth. The irrigation network was found to promote sediment mobilization within the field, but not necessarily sediment losses, due to the strong soil conservation effect of the terrace. Sediment export was rather limited and unlikely to negatively affect soil quality inside the field, but could be relevant for downstream contamination with phosphorus or pesticides attached to soil particles. Published data indicates higher erosion in plantation forests, especially after recurrent disturbances such as management operations and wildfires. In any case, the dataset of this study is somewhat limited, especially in time, opening the door for further studies aiming at a better understanding of the "águas de lima" system and its role in hydrological and sediment connectivity in northwestern Iberian landscapes. In particular, there is a need for further information on soil moisture for the entire soil profile, on irrigation practices and on the hydrological and erosion response behavior of these systems during stronger storms with infrequent return periods.

Acknowledgements

This work was funded by the Portuguese Foundation for Science and Technology within the framework of project ERLAND: "Direct and indirect impacts of climate change on soil erosion and land degradation in Mediterranean watersheds" (FCOMP-01-0124-FEDER-008534), the post-doctoral fellowships attributed to J.P. Nunes (SFRH/BPD/39721/2007 and SFRH/BPD/87571/2012), and funding for the CESAM centre (UID/AMB/50017), co-funded by the European Social Fund and the European Regional Development Fund within the PT2020 Partnership Agreement and Compete 2020. Additional funding was granted by COST (European Cooperation in Science and Technology) through Action ES1306 CONNECTEUR.

References

Alonso-Sarría, F., Martínez-Hernández, C., Romero-Díaz, A., Cánovas-García, F., Gomariz-Castillo, F., 2015. Main environmental features leading to recent land abandonment in Murcia region (southeast Spain). L. Degrad. Dev. https://doi.org/10.1002/ldr.2447

APHA, 1998. Standard Methods for Examination of Water and Wastewater, 20th ed. American Public Health Association (APHA), Washington, D.C.

Blondel, J., 2006. The 'Design' of Mediterranean Landscapes: A Millennial Story of Humans and Ecological Systems during the Historic Period. Hum. Ecol. 34, 713–729. https://doi.org/10.1007/s10745-006-9030-4

Boix-Fayos, C., Martínez-Mena, M., Calvo-Cases, a., Castillo, V., Albaladejo, J., 2005. Concise review of interrill erosion studies in SE Spain (Alicante and Murcia): Erosion rates and progress of knowledge from the 1980's. L. Degrad. Dev. 16, 517–528. https://doi.org/10.1002/ldr.706

Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P., 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. Earth Surf. Process. Landforms 40, 177–188. https://doi.org/10.1002/esp.3635

Bracken, L.J., Wainwright, J., Ali, G.A., Tetzlaff, D., Smith, M.W., Reaney, S.M., Roy, A.G., 2013. Concepts of hydrological connectivity: Research approaches, pathways and future agendas. Earth Sci. Rev. 119, 17–34. https://doi.org/10.1016/j.earscirev.2013.02.001

Cerdà, A., 1997. Soil erosion after land abandonment in a semiarid environment of southeastern Spain. Arid Soil Res. Rehabil. 11, 163–176. https://doi.org/10.1080/15324989709381469

Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.J.P.M., Raclot, D., Ionita, I., Rejman, J., Rousseva, S., Muxart, T., Roxo, M.J., Dostal, T., 2010. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. Geomorphology 122, 167–177. https://doi.org/10.1016/j.geomorph.2010.06.011

Ferreira, A.J.D., Coelho, C.O.A., Ritsema, C.J., Boulet, A.K., Keizer, J.J., 2008. Soil and water degradation processes in burned areas: lessons learned from a nested approach. Catena 74, 273–285. https://doi.org/10.1016/j.catena.2008.05.007

Ferreira, C.G., 1997. Erosão hídrica em solos florestais. Estudo em povoamentos de Pinus Pinaster e Eucalyptus Globulus em Macieira de Alcôba - Águeda. Rev. da Fac. Let. da Univ. do Porto - Geogr. I Série XII/XIII, 145–244.

Gallart, F., Llorens, P., Latron, J., 1994. Studying the role of old agricultural terraces on runoff generation in a small Mediterranean mountainous basin. J. Hydrol. 159, 291–303. https://doi.org/10.1016/0022-1694(94)90262-3

García-Ruiz, J.M., Lana-Renault, N., 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region – A review. Agric. Ecosyst. Environ. 140, 317–338. https://doi.org/10.1016/j.agee.2011.01.003

Giménez, R., Casalí, J., Grande, I., Díez, J., Campo, M., Álvarez-Mozos, J., Goñi, M., 2012. Factors controlling sediment export in a small agricultural watershed in Navarre (Spain). Agric. Water Manag. 110, 1–8. https://doi.org/10.1016/j.agwat.2012.03.007

Govers, G., 1990. Empirical relationships for the transport capacity of overland flow, in: Erosion, Transport and Deposition Processes (Proceedings of the Jerusalem Workshop, March-April 1987). IAHS Publ. no. 189, pp. 45–63.

Hawtree, D., Nunes, J.P., Keizer, J.J., Jacinto, R., Santos, J., Rial-Rivas, M.E., Boulet, A.-K., Tavares-Wahren, F., Feger, K.-H., 2015. Time series analysis of the long-term hydrologic impacts of afforestation in the Águeda watershed of north-central Portugal. Hydrol. Earth Syst. Sci. 19, 3033–3045. https://doi.org/10.5194/hess-19-3033-2015

Hooke, J.M., 2006. Human impacts on fluvial systems in the Mediterranean region. Geomorphology 79, 311–335. https://doi.org/10.1016/j.geomorph.2006.06.036

IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps (No. 106). Food and Agriculture Organization of the United Nations, Rome.

Kamphorst, E.C., Jetten, V., Guérif, J., Pitkänen, J., Iversen, B.V., Douglas, J.T., Paz, A., 2000. Predicting Depressional Storage from Soil Surface Roughness. Soil Sci. Soc. Am. J. 64, 1749. https://doi.org/10.2136/sssaj2000.6451749x

Kirkby, M.J., Bracken, L.J., Shannon, J., 2005. The influence of rainfall distribution and morphological factors on runoff delivery from dryland catchments in SE Spain. Catena 62, 136–156. https://doi.org/DOI: 10.1016/j.catena.2005.05.002

Latron, J., Gallart, F., 2007. Seasonal dynamics of runoff-contributing areas in a small mediterranean research catchment (Vallcebre, Eastern Pyrenees). J. Hydrolology 335, 194–206. https://doi.org/10.1016/j.jhydrol.2006.11.012

Li, X.H., Yang, J., Zhao, C.Y., Wang, B., 2014. Runoff and sediment from orchard terraces in southeastern China. L. Degrad. Dev. 25, 184–192. https://doi.org/10.1002/ldr.1160

Llorens, P., Queralt, I., Plana, F., Gallart, F., 1997. Studying solute and particulate sediment transfer in a small Mediterranean mountainous catchment subject to land abandonment. Earth Surf. Process. Landforms 22, 1027–1035. https://doi.org/10.1002/(SICI)1096-9837(199711)22:11<1027::AID-ESP799>3.0.CO;2-1

Maetens, W., Poesen, J., Vanmaercke, M., 2012. How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean? Earth Sci. Rev. 115, 21–36. https://doi.org/10.1016/j.earscirev.2012.08.003

Martins, M.A.S., Machado, A.I., Serpa, D., Prats, S.A., Faria, S.R., Varela, M.E.T., González-Pelayo, Ó., Keizer, J.J., 2013. Runoff and inter-rill erosion in a Maritime Pine and a Eucalypt plantation following wildfire and terracing in north-central Portugal. J. Hydrol. Hydromechanics 61, 261–268. https://doi.org/10.2478/johh-2013-0033

Morgan, R.P.C., 2005. Soil Erosion and Conservation. Blackwell Publishing, Oxford.

Pereira, S., Bateira, C., Hermenegildo, C., Seixas, A., 2007. Análise comparativa dos processos de escoamento desenvolvidos em terraços agrícolas de áreas com granitóides e metassedimentos (a comparative analysis of runoff processes developed in agricultural terraces in granites and metassedimentar areas). Publicações da Assoc. Port. Geomorfólogos V, 121–132.

Ribeiro, O., 1945. Portugal, o Mediterrâneo e o Atlântico. Estudo Geográfico. Coimbra Editora Lda., Coimbra.

Rodríguez-Blanco, M.L., Taboada-Castro, M.M., Taboada-Castro, M.T., 2013. Linking the field to the stream: Soil erosion and sediment yield in a rural catchment, NW Spain. Catena 102, 74–81. https://doi.org/10.1016/j.catena.2010.09.003

Salesse, E., 2003. Os que “sabiam” e os que “andam baralhados”: funcionamento técnico e social de um regadio (the ones who “knew” and the ones who “are confused”: social and technical functioning of an irrigation network). Etnográfica VII, 33–61.

Santos, J.M., Verheijen, F.G.A., Tavares Wahren, F., Wahren, A., Feger, K.-H., Bernard-Jannin, L., Rial-Rivas, M.E., Keizer, J.J., Nunes, J.P., 2016. Soil water repellency dynamics in pine and eucalypt plantations in portugal - a high-resolution time series. L. Degrad. Dev. 27, 1334–1343. https://doi.org/10.1002/ldr.2251

Shakesby, R.A., 2011. Post-wildfire soil erosion in the Mediterranean: Review and future research directions. Earth-Science Rev. 105, 71–100. https://doi.org/10.1016/j.earscirev.2011.01.001

Stanchi, S., Freppaz, M., Agnelli, A., Reinsch, T., Zanini, E., 2012. Properties, best management practices and conservation of terraced soils in Southern Europe (from Mediterranean areas to the Alps): A review. Quat. Int. 265, 90–100. https://doi.org/10.1016/j.quaint.2011.09.015

van Genuchten, M.T., 1980. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Sci. Soc. Am. J. 44, 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x