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Runoff, erosion, and water quality of agricultural watersheds in central Navarre (Spain)

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ABSTRACT

Two experimental watersheds, La Tejería (1.69 km^2) and Latxaga (2.07 km^2), appointed by the Government of Navarre (Spain) for assessing the effect of agricultural activities on the environment, were monitored during 10 years (1996–2005). Both watersheds are roughly similar with regard to soils, climate (humid sub Mediterranean) and land use (almost completely cultivated with winter grain crops). The first results for both sites on runoff, exported sediment, nitrate and phosphate are presented.

Most runoff, sediment, nitrate and phosphate yields were generated during winter, when variability was also the highest of the whole year.

La Tejería had much higher sediment concentrations and sediment yield than Latxaga. Nitrate concentrations were also significantly higher at La Tejería, with values constantly over the critical threshold ($>50\ mg\ NO_3\ l^{-1}$). However, phosphate concentrations were similar in both watersheds and corresponded to water with a significant risk of eutrophication. Differences in watershed behaviour could be mainly due to differences in morphology, topography, and amount of stream channel vegetation between both sites.

This is an unprecedented research for the region and the generated dataset is of paramount importance for research issues such as hydrology, erosion and water quality. The results highlight the complexity of Mediterranean agricultural landscapes and the need for further analyses to better ascertain the processes behind them.

1. Introduction

Non-irrigated arable lands cover approximately 30% of the area of Europe (EEA, 2005) and an important proportion of the world as well (FAOSTAT, 2005). These areas are frequently cultivated with crops of great social and economic importance to many regions. The peculiarity of the conventional arable land cropping system is that the soil surface remains uncovered during long periods of time, corresponding to the soil preparation and crop establishment phases, which frequently occur during the wettest seasons. As a result, soil erosion problems are a common feature of these areas (Casalí et al., 1999; Poesen et al., 2003; Auzet et al., 2004; De Santisteban et al., 2006). Erosion causes soil degradation and also severely affects water resource

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quality (PAP/RAC, 1997), which nowadays constitutes a very serious threat to the environment. It is thought that a quarter of Europe's agricultural land exhibits some erosion risk (EEA, 2005).

Furthermore, arable lands are a major source of water pollutants (OECD, 2001; Iital et al., 2005; Angás et al., 2006). The latest data on the quality of European water resources highlight the detrimental impact of over-fertilization on the quality of ground and surface waters at present (EEA, 2005). The so-called diffusive or non-point-source pollution, especially, is predominant in agricultural areas, with nitrate and phosphate being the main problem. For instance, it has been reported that agriculture is the source of 46–87% of the nitrate and 20–40% of the phosphate incorporated into European continental waters (EEA, 1999). Diffusive contamination pollutes waters, causes their eutrophication and offers significant health risks originating from high agrochemical concentrations in drinking water. As a consequence, most governments and environment agencies in developed countries have recently created directives and regulations to reduce the presence of nutrients (mainly nitrate) in surface and ground water (EC, 1991; US EPA, 2000). However, their implementation has not been completely successful so far due to several technical and policy difficulties such as the designation of vulnerable areas, the monitoring and assessment of the effectiveness of measures or their contraposition to agricultural productivity criteria (EEA, 1999).

In this context, the need for clear and accurate soil erosion and water quality measurements in agricultural areas is vital as a reliable basis for any understanding of the underlying processes, the assessment of their significance and the consequent development of prevention plans (PAP/RAC, 1997; EEA, 1999). Measurements can be obtained at plot, small watershed or large watershed scale. At a plot scale, these measurements are usually adequate enough to analyze processes and evaluate soil conservation practices or erosion models. However, obtaining representative information about larger areas can be impossible with the plot approach (Parsons et al., 2004), and in large watersheds too, defining sediment and pollutant transport processes can entail a high degree of complexity (De Vente et al., 2006), thus failing to identify the sediment and nutrient sources and the significant processes. Therefore, the monitoring of erosion and water quality variables can best be approached in small sized watersheds (0.5–2.0 km^2) (PAP/RAC, 1997; Hyer et al., 2001; Quinn, 2004). Several initiatives have been conducted to develop soil erosion and water quality measuring station networks at the watershed scale over agricultural landscapes (Walling and Webb, 1996; Renard et al., 2003).

Non-irrigated arable lands also cover an important part of Spain, approximately 25% (EEA, 2005), as well as a significant area of the region of Navarre, approximately 30% (Gobierno de Navarra, 2001). Furthermore, soil erosion phenomena are a common feature of Navarre's agricultural lands (Casalí et al., 1999; De Santisteban et al., 2006). As a result, the Department of Agriculture, Livestock and Food of the Government of Navarre decided to establish a network of experimental agricultural watersheds. The main objective of the network was to provide data for assessing the effect of agricultural activity on the water resources, and, consequently, for identifying and implementing environmentally sound land management practices. Additionally, the data collected at the experimental watersheds are of great utility for the evaluation of several modelling tools. The experimental watershed network consists of four watersheds. Two of them, Latxaga and La Tejería, are located within high productivity winter grain farming areas, the third watershed, Oskotz, is in an area of intensive cattle-breeding, whereas the fourth, namely Landazuria, is an irrigated, intensively cultivated area. The Latxaga and La Tejería watersheds have been investigated since 1995, Oskotz since 2000, and Landazuria since the present year. The instrumentation in each watershed includes: one automatic meteorology station; several non-recording rainfall gauges distributed throughout the watershed; and one discharge measuring station where discharge, turbidity and water quality parameters are measured (Del Valle de Lersundi and Donézar, 1995; Donézar and Del Valle de Lersundi, 2001). The geological material is impervious within each watershed, which ensures a suitable control of the water balance.

In this paper, data recorded at Latxaga and La Tejería watersheds are analyzed and studied in detail. These watersheds can be considered as being representative of wide areas of Navarre and Spain as regards their morphology, soils, climate, land use and management. It should be noted that the information already available covers a 9-year period, with continuous observations from 1 September 1996 to 31 August 2005. Rainfall, runoff, sediment, nitrate and phosphate data are presented and discussed.

The two remaining watersheds, i.e., Oskotz and Landazuria, are not analyzed herein. The reason for that is twofold. First, we still have a dataset of these watersheds with an insufficient amount of recorded years. Secondly, the land uses of these watersheds are much different between them and between those at La Tejería and Latxaga. The fact that, La Tejería and Latxaga share a similar land use facilitates our study and analysis as a first approach.

The main objectives were (1) to analyze the behaviour of agricultural experimental watersheds in terms of discharge, sediment, nitrate and phosphate yield and concentrations, and (2) to study the controlling factors underpinning that behaviour.

2. Description of the experimental watersheds

2.1. Latxaga watershed

Latxaga watershed covers an area of 207 ha and is located in the central eastern part of Navarre (Spain) (Fig. 1). The geographical coordinates of the watershed outlet are 42°47′7.5″N and 1°26′11.4″W. The main morphological characteristics of the watershed are shown in Table 1. Its climate is humid submediterranean, with an average annual precipitation of 835 mm, distributed over 95–100 days of rainfall, and an average annual temperature of 12 °C (Gobierno de Navarra, 2001). The valley bottom minimum slopes are about 5–7%, whereas the hill slopes can reach up to 30%. Geologically, the area is underlined by clay marls and Pamplona grey marls (Gobierno de Navarra, 1997). A detailed soil map of the Latxaga watershed is provided in Fig. 2, and information on soil properties in Table 2. The prevailing soil class is *Paralitic*

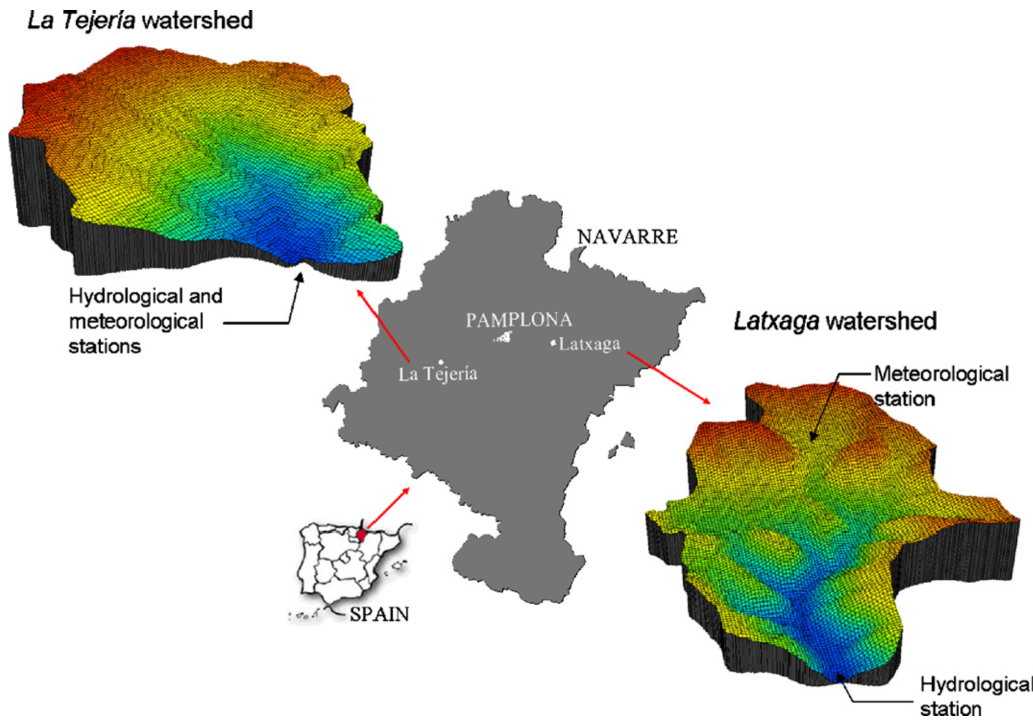

Fig. 1 – Latxaga and La Tejería watersheds are part of the experimental agricultural watershed network of the Government of Navarre. Both are located in the central part of Navarre.

Xerorthent covering 43% of the watershed, and located on eroded hillslopes. These soils are shallow (less than 0.5 m deep) and the upper horizon is silty-clay-loam. *Fluventic Haploxerept* soils cover 36% of the watershed area, and are located on swales and hillslopes where eroded soil accumulates. These soils are deeper (over 1 m deep) and the upper horizon is also silty-clay-loam. The estimated average soil bulk density and porosity of the top horizon are around 1.26 Mg m^{-3} and 0.52, respectively (Rawls and Brakensiek, 1989). The soil erodibility factor of the Universal Soil Loss Equation (Wichmeier and Smith, 1978), K_{USLE}, of the top horizon is around 0.48 (t m^2 h)/(ha hJ cm) (hJ = hectojoule), and the area-weighted average soil depth is 1.03 m. The estimated watershed hydraulic conductivity at saturation (Rawls and Brakensiek, 1989) is around 2.01 mm h^{-1}.

The watershed is almost completely cultivated with winter grain (wheat and barley usually cover 80% or 90% of the total area). Average yields are about 3500–4000 kg ha^{-1} on the hillslopes and around 5500 kg ha, or even higher, in the swales. Tillage is conventional, and frequently parallel to contour lines. Tillage practices are performed in such a way that a vegetation strip around the streams is maintained, thus allowing the growth of sometimes dense riparian vegetation.

Fertilization is performed following the indications given by the technical advisory service of the Government of Navarre (Instituto Técnico de Gestión Agrícola). Nitrogen is applied twice, first at the tillering initiation stage (approximately 15 January) and second at the end of the tillering stage (approximately 15 March). Most common fertilisers are diammonium phosphate (DAP) and urea. The annual nitrogen dose applied is approximately 230 kg N ha^{-1}. Also, every 3 years, an additional phosphorus application is performed at the sowing stage to restore the soil from crop extractions. This consists of an approximate amount of 165 kg ha of DAP.

2.2. *La Tejería watershed*

La Tejería watershed covers an area of 169 ha and is located in the central western part of Navarre (Fig. 1). The geographical coordinates of the watershed outlet are 42°44′10.6″N and 1°56′57.2″W. Morphological characteristics of La Tejería watershed are detailed in Table 1. Its climate is also humid submediterranean, with an average annual precipitation of approximately 725 mm, distributed over 105 days of rainfall (Gobierno de Navarra, 2001). The average annual temperature is around 13 °C. Slopes are very homogeneous with an average value of 15%. The watershed is underlined by marls and

Table 1 – Some morphological characteristics of La Tejería and Latxaga watersheds

	Latxaga	La Tejería
Area (km^2)	2.07	1.69
Perimeter (km)	6.67	5.46
Total channel length (km)	5.38	3.20
Minimum elevation (m)	504	496
Maximum elevation (m)	639	649
Av. slope (%)	19.3	14.8
Av. (permanent) channel slope (%)	12.4	14.6
Gravelius index	1.30	1.17
Shape Factor	0.44	0.85
Drainage density (km km^{-2})	2.61	1.91

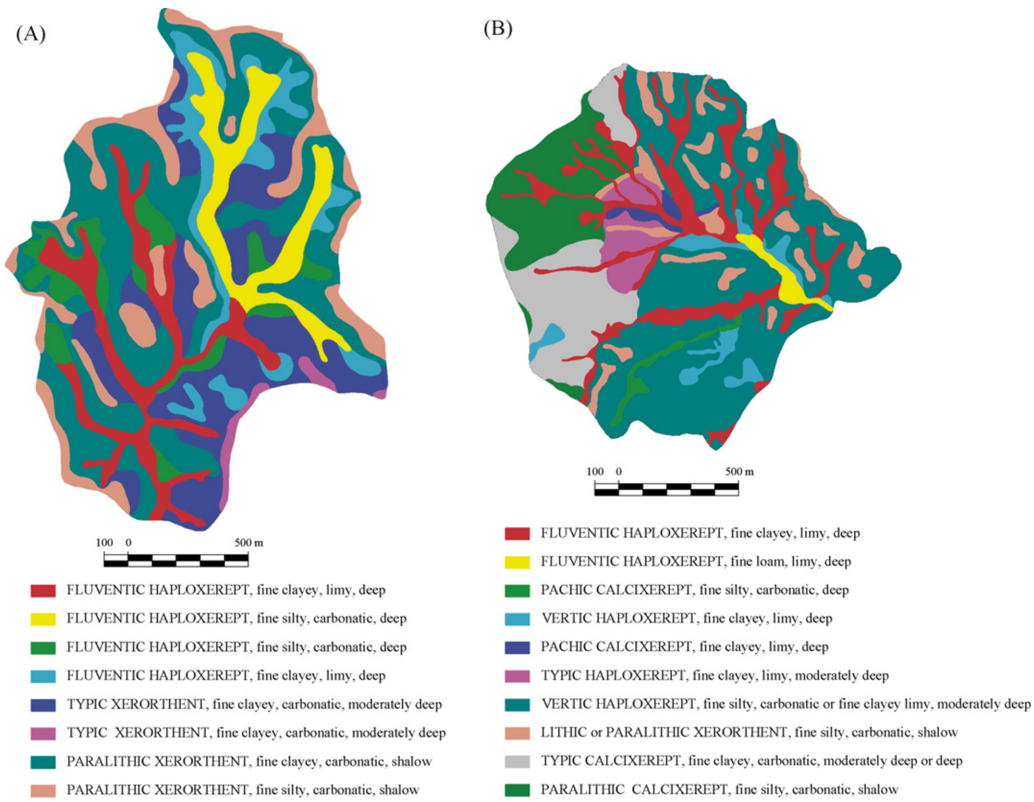

Fig. 2 – Soil maps of (A) Latxaga and (B) La Tejería watersheds.

sandstones of continental facies (Gobierno de Navarra, 1997). A detailed soil map of the La Tejería watershed is provided in Fig. 2, and a description of the soil properties is given in Table 2. The prevailing soil class is *Vertic Haploxerept* covering 41% of the watershed, and located on eroded hillslopes. These soils are relatively shallow (0.5–1.0 m deep) and the upper horizon has a clayey-silty texture. The estimated soil bulk density and porosity are around 1.37 Mg m^{-3} and 0.48, respectively (Rawls and Brakensiek, 1989). K_{USLE} erodibility of the top horizon (Wichmeier and Smith, 1978) is around 0.38

Table 2 – Main soil characteristics for Latxaga and La Tejería watersheds

Classification (USDA Soil Taxonomy, 1998)	Geomorphology	Upper horizon texture (USDA)	Area (ha)	Organic matter content (%)	Soil depth (m)
Latxaga watershed					
Fluventic Haploxerept	Swales	Loam-clay-silty	21.99	1.82	>1
Fluventic Haploxerept	Swales	Loam-silty	20.13	1.80	>1
Fluventic Haploxerept	Accumulation hillslopes	Loam-clay-silty	14.58	1.89	>1
Fluventic Haploxerept	Accumulation hillslopes	Loam-clay-silty	17.39	1.48	>1
Typic Xerorthent	Erosion hillslopes	Loam-clay-silty	41.37	2.48	>1
Typic Xerorthent	Erosion hillslopes (gentle)	Loam-clay-silty	2.71	1.92	>1
Paralithic Xerorthent	Erosion hillslopes	Loam-clay-silty	65.67	1.81	<0.5
Paralithic Xerorthent	Erosion hillslopes	Loam-clay-silty	23.15	1.51	<0.5
La Tejería watershed					
Fluventic Haploxerept	Swales	Clay-silty	26.76	1.99	>1
Fluventic Haploxerept	Swales	Loam-clay-silty	2.58	1.99	>1
Pachic Calcixerept	Swales	Loam-clay-silty	2.35	1.58	>1
Vertic Haploxerept	Accumulation hillslopes	Clayey	6.39	1.77	>1
Pachic Calcixerept	Accumulation hillslopes	Clay-silty	1.87	1.74	>1
Typic Haploxerept	Erosion hillslopes	Loam-clayey	6.46	1.16	0.5–1
Vertic Haploxerept	Erosion hillslopes	Clay-silty	69.38	1.05	0.5–1
Lithic/Paralithic Xerorthent	Erosion hillslopes (gentle)	Loam-clayey	11.64	3.75	<0.5
Typic Calcixerept	Erosion hillslopes	Clay-silty	21.69	2.31	>0.5
Paralithic Calcixerept	Erosion hillslopes	Loam-clay-silty	19.78	1.45	<0.5

Table 3 – Some characteristics of precipitation and discharge data recorded at Latxaga and La Tejería watersheds

	Accumulated precipitation (mm)		Accumulated discharge (mm)		Runoff coefficient (%)	
	Mean	σ	Mean	σ	Mean	σ
Latxaga						
Autumn	236	70	7	11	3	5
Winter	2101	116	154	113	53	23
Spring	192	59	53	54	29	26
Summer	132	94	5	7	3	4
Annual	770	169	244	107	30	14
La Tejería						
Autumn	191	65	18	22	8	8
Winter	223	134	112	61	42	20
Spring	161	18	40	38	24	21
Summer	117	72	5	3	4	3
Annual	691	180	203	48	23	10

Mean refers to the average and σ to the standard deviation for each time period.

(t m^2 h)/(ha hJ cm). The area-weighted average soil depth is 0.81 m, whereas estimated watershed hydraulic conductivity at saturation (Rawls and Brakensiek, 1989) is around 1.07 mm h^{-1}.

Land use, crop productivity and soil management practices are very similar to those described for the Latxaga watershed, with cereal crops covering usually more than 90% of the total area. However, the stream beds and banks within the La Tejería watershed are poorly vegetated, favouring the occurrence of bank erosion processes. Fertilization is also similar to that of the Latxaga watershed. Two applications are also performed at the initiation and ending of the tillering stage, but the total annual amount of N applied is significantly lower than at Latxaga, with an approximate value of 150 kg N ha^{-1}.

2.3. *Measurement devices and procedures*

One automatic meteorology station was installed in each watershed (Fig. 1) (Del Valle de Lersundi and Donézar, 1995; Donézar and Del Valle de Lersundi, 2001). Air temperature, rainfall, relative air moisture, wind speed and direction, soil temperature, and solar radiation were recorded on a 10 min basis. Additionally, one hydrology station was installed at each watershed outlet (Fig. 1), where the water level and

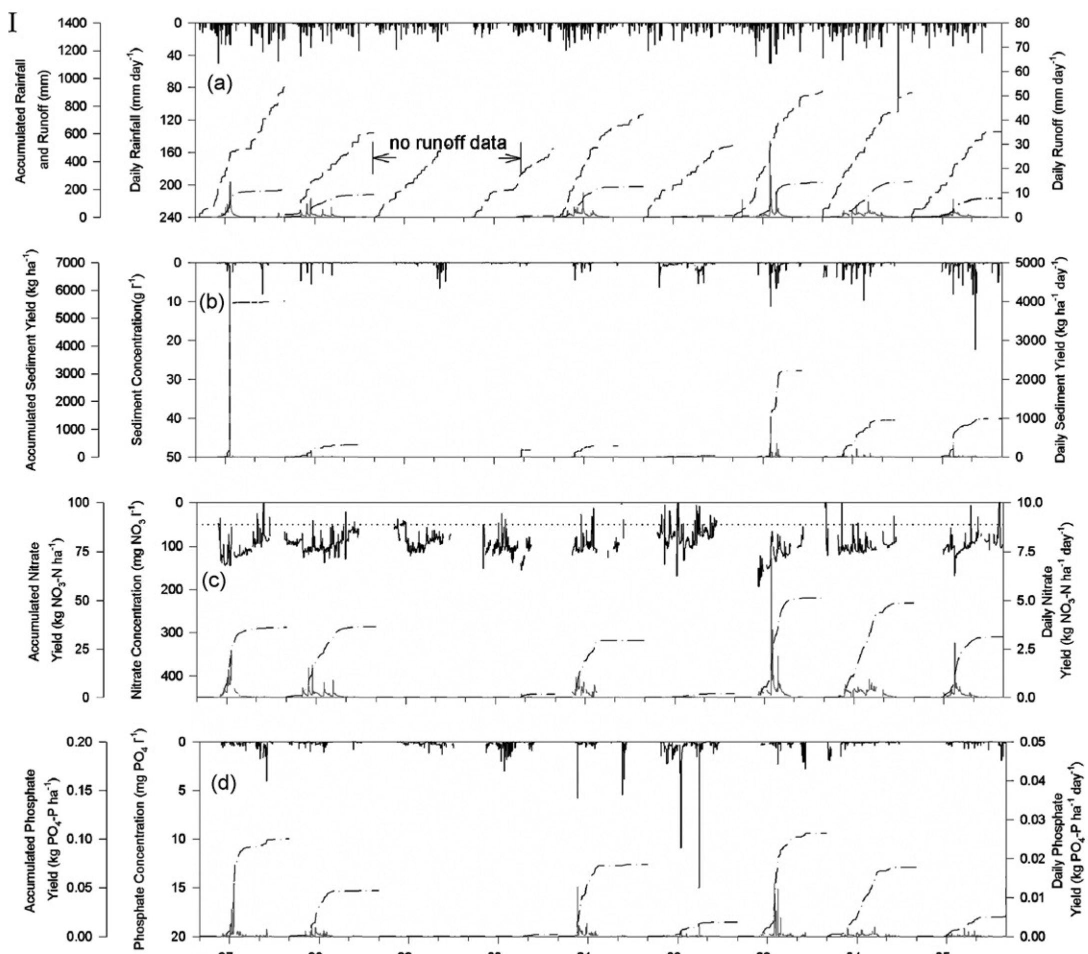

Fig. 3 – Results of (a) rainfall and runoffs data, (b) sediment, (c) nitrate and (d) phosphate concentrations and yields recorded at (I) la Tejería and (II) Latxaga.

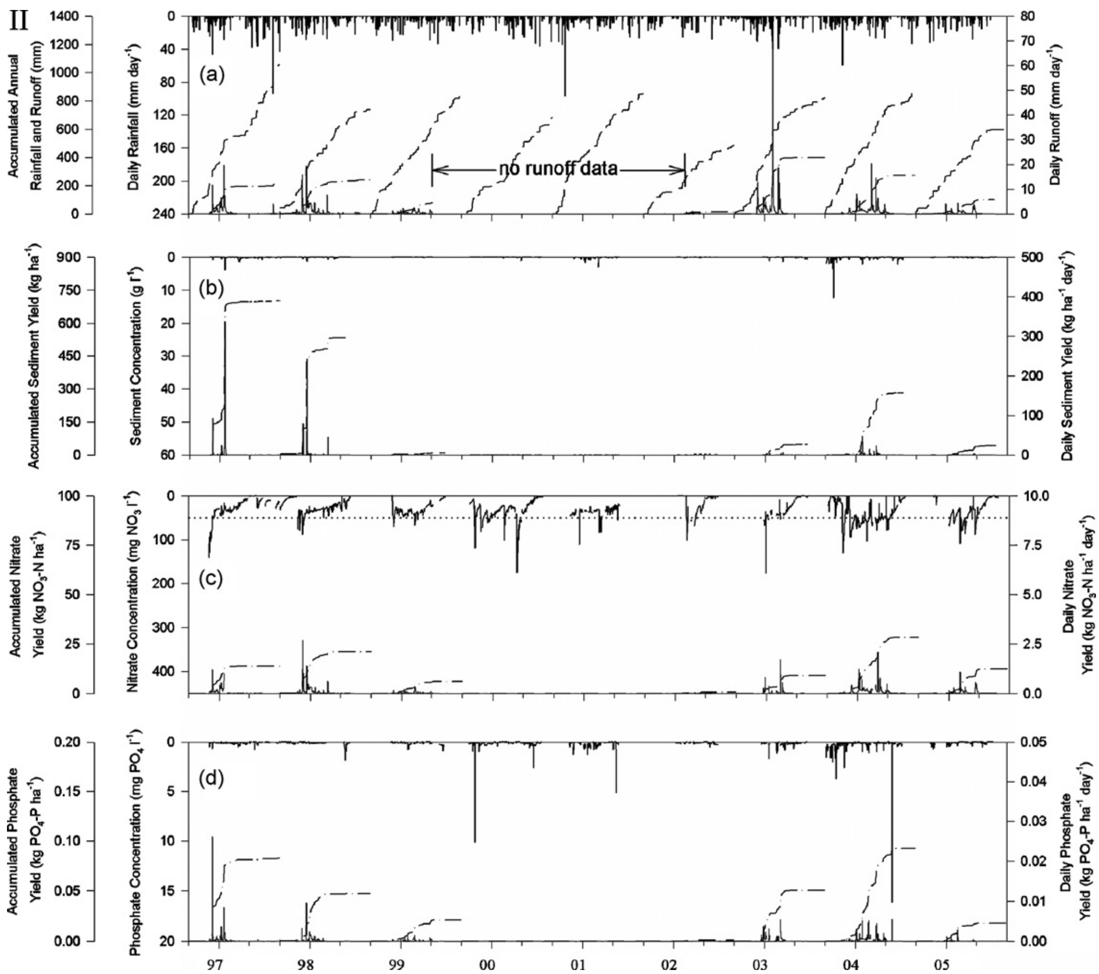

Fig. 3. (Continued).

turbidity were recorded also every 10 min. The discharge measurement device consisted of a triangular profile flat-V weir (Bos, 1978). This hydraulic structure was selected, among other reasons, because its design permitted the sediment to pass the control section. Discharge was calculated from water level data, which were monitored using a pressure probe. Water discharge was also directly measured for verification using a propeller-type current meter and triangular and rectangular sharp-crested weirs (Bos, 1978). All measurement methods yielded consistent results.

Water samples were taken every 6 h from a hemispheric hollow, 0.66 m in diameter, made in the downstream face of the triangular profile flat-V weir. For this purpose, an automatic programmable sampler was used, consisting of

Table 4 – Rainfall characteristics for categorized precipitation events at both watersheds

Rainfall variables	Rainfall events category (mm)						
	0–10	10–20	20–30	30–40	40–50	50–60	>60
Latxaga							
Number of events	928	138	40	19	7	3	5
Av. rainfall depth (mm)	2.5	14.4	24.5	35.2	43.5	55.5	75.3
Av. storm duration (h)	7.1	20.3	26.6	36.3	30.8	43.9	58.8
Av. rainfall erosivity (EI_{30})[a] (J mm m^{-2} h^{-1})	108	1837	2646	6847	4702	36,672	32,154
La Tejería							
Number of events	986	136	46	18	14	2	1
Av. rainfall (mm)	2.5	13.8	24.4	35.4	45.1	51.3	99.3
Av. storm duration (h)	7.1	16.5	27.5	35.5	35.2	36.2	11.2
Av. rainfall erosivity (EI_{30})[a] (J mm m^{-2} h^{-1})	110	1690	3043	8006	10,060	41,061	157,588

[a] EI_{30} according to Brown and Foster (1987).

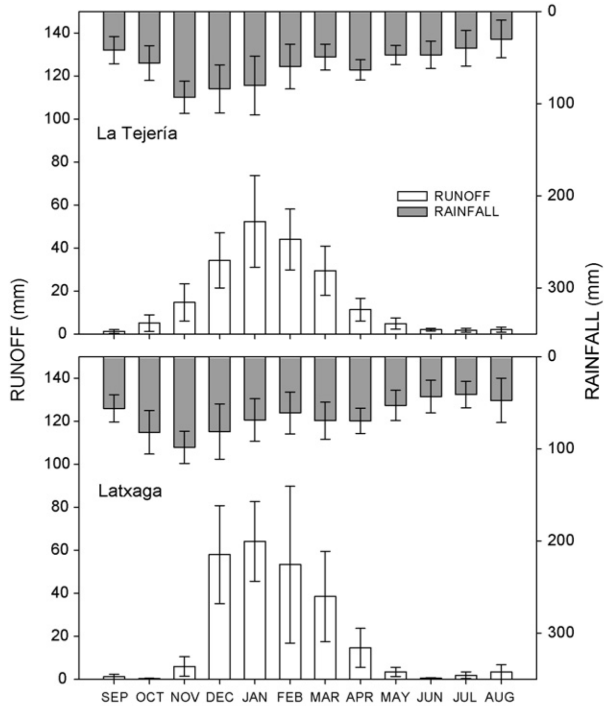

Fig. 4 – Monthly average rainfall and runoff at La Tejería and Latxaga. Vertical bars are standard deviation.

24,500 ml-bottles. Water samples were analyzed following the standard methods for water quality parameters at the Agricultural Laboratory of the Department of Agriculture and Food of the Government of Navarre. Sediment concentration and dissolved nitrate and phosphate concentrations were determined, as well as other chemicals that are not mentioned in this paper (i.e., sulphate, carbonate, potassium, calcium, magnesium and sodium). The four samples collected each day were mixed together prior to analysis, to provide a representative daily average sample for determining sediment and nutrient concentrations (Isidoro et al., 2003). When the water discharge was near zero, the programmable sampler was switched off.

Due to some problems with the water level probes, the discharge data were lost at La Tejería from September 1998 to March 2000, and also at Latxaga from May 1999 to February 2002. Also, some exceptional rainfall-runoff events occurred at both watersheds (05 August 1997 at Latxaga and 07 July 2004 at La Tejería) and could not be recorded since they collapsed the hydrology stations. Finally, rainfall data were lost during some short periods. Those data were restored using the double-mass method (Llamas, 1993) and data from the nearest meteorology stations: Aoiz for Latxaga watershed and Estella for La Tejería watershed (Gobierno de Navarra, 2001), with an r^2 of about 0.98 in both cases.

2.4. *Field survey*

In both watersheds, main erosion features (e.g., gullies, rills) have been identified and monitored in the field since winter 2003/2004 (De Santisteban et al., 2005). Channel cross-sections were measured using different devices depending on the channel size. Rills and small gullies were measured by using a pin profiler as described elsewhere (Casalí et al., 1999). Instead, cross-sections of large gullies were first assimilated to a simple geometric form (e.g., a rectangle) and then horizontal and vertical distances were measured with a ruler. Channel lengths were always measured by using a ruler.

2.5. *Watershed morphometry*

In order to characterize the morphology of the watersheds, two indices (Gravelius Index and shape factor) were used.

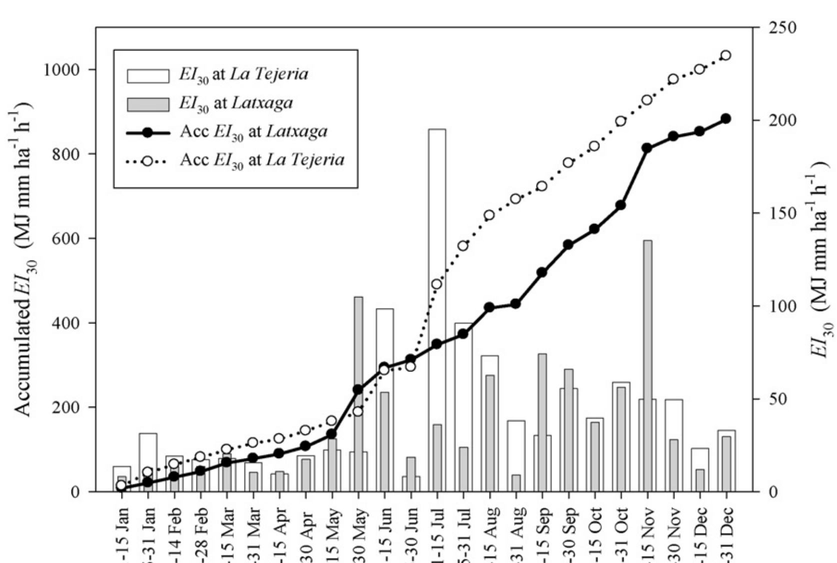

Fig. 5 – Average fortnightly and accumulated average fortnightly values of rainfall erosivity (EI_{30}) at *Latxaga* and *La Tejería* watersheds (average values for the 9-year period studied).

Table 5 – Annual values of sediment, nitrate and phosphate yields, their average values, and the average concentration of these parameters for the whole studied period

Site	Sediment		Nitrate		Phosphate	
	Conc. ($mg\,l^{-1}$)	Yield ($kg\,ha^{-1}\,year^{-1}$)	Conc. ($mg\,l^{-1}$)	Yield ($kg\,ha^{-1}\,year^{-1}$)	Conc. ($mg\,l^{-1}$)	Yield ($kg\,ha^{-1}\,year^{-1}$)
La Tejería						
96/97		5609		156		0.30
97/98		431		158		0.14
98/99		na		na		na
99/00		na		7		0.01
00/01		236		128		0.22
01/02		393		8		0.04
02/03		42		22		0.32
03/04		1336		210		0.21
04/05		1377		135		0.06
Average	383 (316)	1979 (175)	87 (8)	163.6 (65.5)	0.24 (0.1)	0.0085 (0.02)
Latxaga						
96/97		701		67		0.25
97/98		534		92		0.14
98/99		9		26		0.06
99/00		na		na		na
00/01		na		na		na
01/02		2		3		na
02/03		48		60		0.15
03/04		282		123		0.28
04/05		42		54		0.05
Average	128 (80)	290 (238)	27 (5)	73.1 (32.2)	0.16 (0.1)	0.0071 (0.02)

Standard deviation is shown in parentheses.

The Gravelius index, K_c, is defined as (Bendjoudi and Hubert, 2002):

$$K_c = \frac{0.28P}{A^{0.5}} \quad (1)$$

where P is the watershed perimeter (m) and A is the watershed area (m^2). A rather circular watershed has a K_c value close to unity. The longer the watershed, the lower its K_c value is.

The shape factor, K_f, is defined as (Monsalve Sáenz, 1999):

$$K_f = \frac{A}{L^2} \quad (2)$$

where L is the maximum length along the main stream from the outlet to the most distant ridge on the drainage divide (m).

The lower the shape factor value (K_f) is, more likely the occurrence of overflowing is.

3. Data analysis and discussion

3.1. *Rainfall and runoff*

The rainfall patterns of both watersheds are typical for humid Mediterranean climates (Table 3). The inter-annual variability of the precipitation was quite high with the maximum variability observed in winter, and the minimum in spring (Table 3, Fig. 3). At Latxaga, the accumulated annual rainfall ranged from a maximum of 1057 mm (agricultural year 1996–1997) to a minimum of 482 mm (agricultural year 2001–2002), with an average value of 770 mm. La Tejería showed a slightly lower precipitation, from a maximum of 933 mm (agricultural year 1996–1997) to a minimum of 493 (agricultural year 1999–2000), with an average value of 691 mm (Table 3). The rainfall showed a slight seasonal pattern in both watersheds: winter was the wettest period, whereas summer was usually the driest (Table 3, Fig. 4). Yet, precipitation was still significant in this last season with approximately 17% of the annual precipitation (Table 3).

However, and according to the EI_{30} rainfall erosivity index (Morgan, 2005) (EI_{30} is a compound index of kinetic energy of the rain, E, and the maximum 30-min intensity, I_{30}), more than 80% of the registered rain events along the year had a (very) low erosivity ($EI_{30} < 100\,J\,mm\,m^{-2}\,h^{-1}$) (Table 4). In contrast, just few rain events had (very) high erosivity, i.e., two or three orders of magnitude higher than the above (Table 4). High erosivity rainfalls occurred mainly during summer, at La Tejería, and autumn and spring, at Latxaga (Fig. 5). As discuss below, the erosivity of the rain did not fully account for the total average sediment yield registered at both watersheds.

On the other hand, average runoff discharges at both watersheds along the year follow a roughly similar pattern than that of the precipitations (Fig. 4). Like precipitation, the inter-annual variability of the discharges was high with the maximum and minimum variability in winter, and in spring, respectively. Accumulated annual discharge ranged between 100 and 396 mm for Latxaga and between 11.4 and 257 mm for La Tejería, with average values of 244 and 203, respectively (Table 3). Moreover, at Latxaga, the annual maximum daily

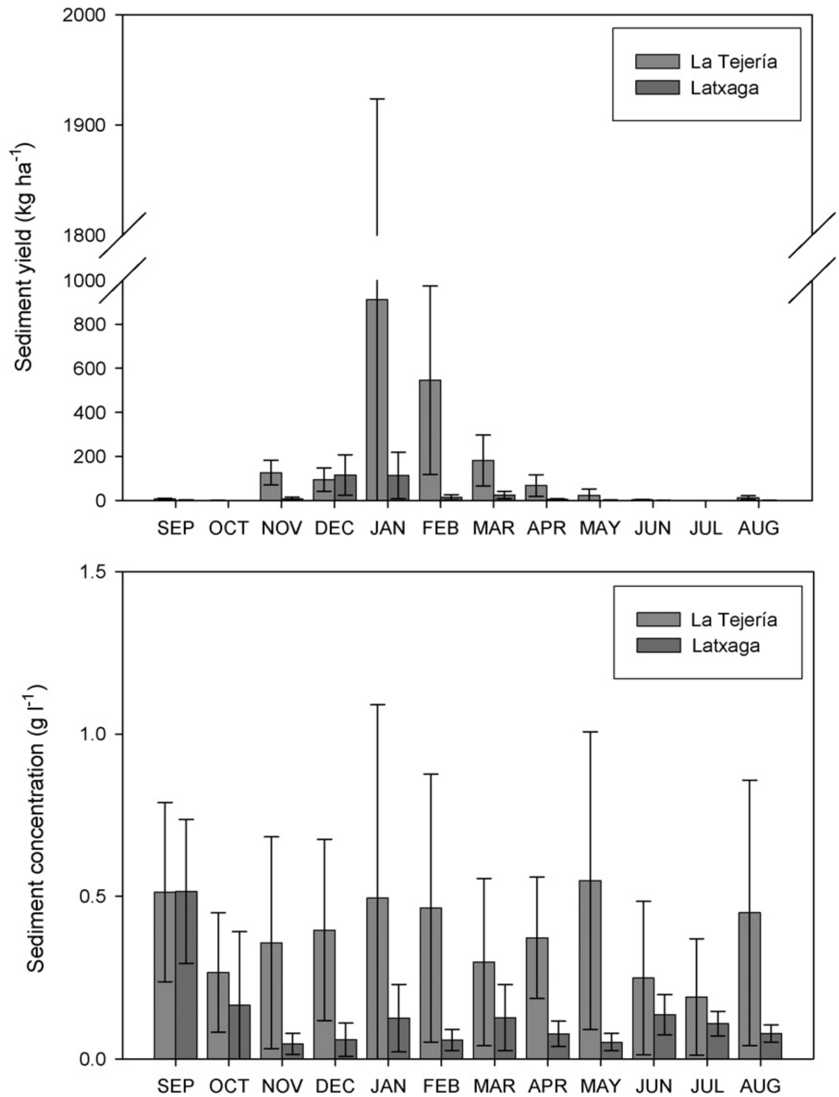

Fig. 6 – Monthly average sediment yield and sediment concentration values at La Tejería and Latxaga.

mean discharge ranged between 0.461 $m^3 s^{-1}$ recorded on 18 December 1998 and 1.595 $m^3 s^{-1}$ on 2003/02/04. At La Tejería, these values ranged between 0.153 $m^3 s^{-1}$ recorded on 17 December 1997 and 0.614 $m^3 s^{-1}$ on 30 January 2003. Similar also to precipitation, runoff values showed a seasonal behaviour in both watersheds (Table 3, Fig. 4), most of it occurring during winter time (Table 3). During summer, vegetation favoured canopy interception and evapotranspiration; this led to some extent to an important decrease in runoff. Furthermore, during the autumn discharges were usually scant in both watersheds, though precipitation amount was still rather high. Therefore, soil moisture tended to increase during autumn.

3.2. *Sediment concentration and yield*

Regarding sediment concentration and yield, the two watersheds behaved in a different way (Table 5, Figs. 3 and 6). The annual sediment concentration was about thrice higher at La Tejería than at Latxaga (Table 5). Likewise, the annual sediment yield at La Tejería had an average value about six times as high as than that of Latxaga (Table 5).

Directly and mainly controlled by rainfall events, sediment concentration and sediment yield also presented a large interannual variability, e.g. the annual sediment yield reached maximum values of 5 and 0.7 t ha^{-1} $year^{-1}$ at La Tejería and Latxaga, respectively (Table 5). Sediment yield mainly occurred during winter and beginning of springtime (Fig. 6) when, as mentioned above, most of the rainfalls had low erosivity (Fig. 5). The most likely explanation for this is the following. During winter, soils in both watersheds are usually almost saturated and the vegetation cover is scarce. This led to large runoff rates (Table 3) flowing over unprotected and then vulnerable soils. On the contrary, the higher erosivities of summer rainfalls (Fig. 5) were mainly offset by more protected and drier soils (i.e., with more infiltration capacity). On the other hand and curiously, most of the annual sediment yield at both sites was a result of just a few precipitations events. A similar response was observed in ephemeral gully systems in Southern Navarre (Casalí et al., 1999; De Santisteban et al.,

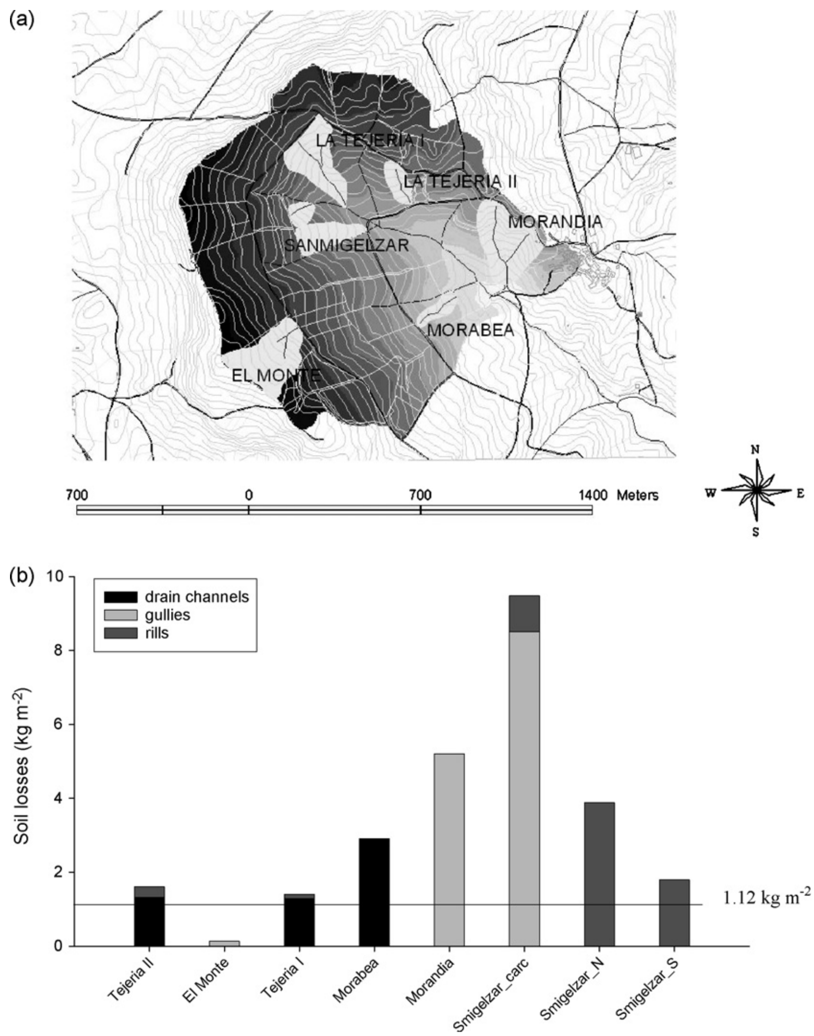

Fig. 7 – Monitored erosion features at *La Tejería* watershed during agricultural year 2003–2004. Several sub-watersheds showed severe soil losses (a) mainly due to ephemeral gullies, enlarged drainage channels and rills (b). The maximum soil loss tolerance threshold (Schertz, 1983) is shown.

2006), where most soil losses occurred in only one event in early winter. However, erosion rates at these watersheds seemed to be lower than those measured in areas of Southern Navarre where soils are more erodible (Casalí et al., 1999; De Santisteban et al., 2006). This is in agreement with previous qualitative estimations made by Donézar et al. (1990a,b). Values of sediment yield recorded at La Tejería corresponded to erosion rates likely to be above soil loss tolerance thresholds at least in some sub-watersheds (Schertz, 1983). Therefore, total sediment yield at both watersheds may be mainly explained by the current soil condition rather than by the erosivity of the rain.

On the other hand, a large intra-watershed spatial variability was also registered, mostly at La Tejería. At some small sub-watersheds of La Tejería, soil losses were some years one order of magnitude higher than the average value for the whole watershed (Fig. 7). This was due to the action of observed soil erosion by concentrated flow in these sub-watersheds (Fig. 8). For instance, during the agricultural year 2003/2004, De Santisteban et al. (2005) detected severe concentrated flow erosion in some sub-watersheds at La Tejería. Furthermore, La Tejería was sometimes affected by mass movements such as that one of 1.7 ha that occurred in the spring in 2001 and 2003. In contrast, neither gullies/rills nor mass movements have been observed at Latxaga.

In our opinion, differences between both watersheds in terms of sediment yield may be explained largely by both some morphological characteristics of the watersheds, and different vegetation amount in stream channels. With regard to morphological and topographic differences between watersheds, La Tejería is more circular shaped (see shape factor and Gravelius Index, Table 1), with a smoother topography and a higher general slope gradient of the stream channels than those of the Latxaga watershed. A rather circular shape, flatter topography and higher average slope gradient of stream channels may afford a more efficient removal of watershed precipitations and promote larger peak discharges that tend to reach the outlet simultaneously from all source areas in the watershed. Moreover, the quite complex topography, gentler slopes and larger vegetation of the stream channels at Latxaga

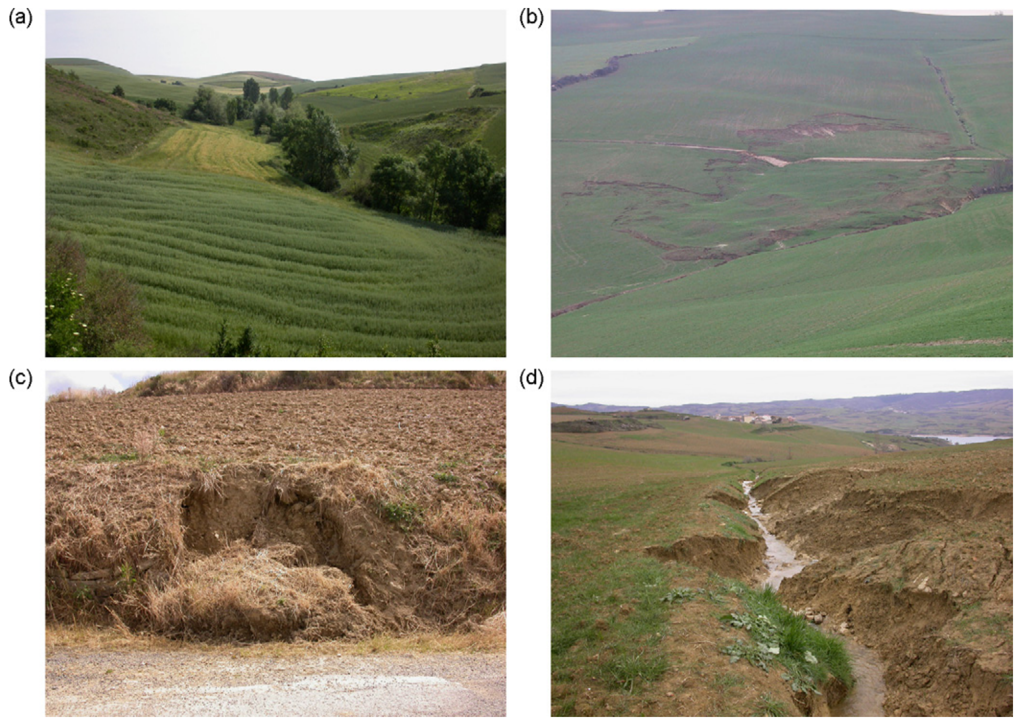

Fig. 8 – Streams are densely vegetated at *Latxaga* watershed (a), whereas at *La Tejería* erosion features are commonly observed, i.e., mass movements (b) and bank erosion processes (c and d) are usual.

(Fig. 8a), should favour the sedimentation of eroded particles at intermediate locations within the watershed. This sedimentation offsets to some extent sediment yield (Parsons et al., 2004).

In order to explore in more details the effect of the watershed morphology, topography as well as of vegetation in stream channels on the total sediment yield, a series of simulations were performed using the event-based model EUROSEM (Morgan et al., 1998). It is obvious that using this model a simplification of the involved hydrologic processes is being made. Nevertheless, we believe this model may help us to estimate to what extent sediment yield at La Tejería is affected by its morphology and vegetation in stream channels. As regards the evaluation of morphology and topography effects, two different watersheds were simulated. One of them, namely W_T, was defined by giving to each parameter (e.g., topographical, hydrological, geological), required by the model, the value determined by Larrañaga et al. (in preparation) to recreate La Tejería watershed. The second watershed, namely W_L, was similar to W_T except for the topographical parameter values, which were instead adapted to the Latxaga watershed. The main input parameter values used in the simulation are shown in Table 6. From the simulation output, it can be seen that the watershed morphology and topography accounted for remarkable changes in sediment yield (Fig. 9). Briefly, if La Tejería had a rather elongated shape and rough topography like the Latxaga's, its total sediment yield would decrease around three to five times, depending on the characteristics of the rain event (Fig. 9). These differences between both watersheds are roughly in agreement with the average sediment yields for all the recorded years (Table 5). Yet, this comparison should be treated with caution since EUROSEM is an event-based model, as mentioned above.

On the other hand, to assess to what extent the lack of vegetation in the stream channels affect total sediment yield, another simulation was performed applying EUROSEM in La Tejería watershed. The total Manning's roughness coefficient, n_{total}, is used in EUROSEM to describe the roughness imparted to flow (Eq. (3)), and it represents the summation of different roughness (friction) factors (Arcment and Schneider, 1989):

$$n_{total} = (n_b + n_1 + n_2 + n_3 + n_4)m \qquad (3)$$

where n_b = base value of n for a straight, uniform, smooth channel in natural materials. n_1 = correction factor for the effect of surface irregularities. n_2 = value for variations in shape and size of the channel cross-section. n_3 = value for obstructions. n_4 = value for vegetation and flow conditions in stream channel. m = correction factor for meandering of the channel.

The model was run several times inputting, in its turn, a different n_4 value in order to simulate different vegetation amounts in the stream channels (Table 7). Consequently, a different n_{total} was defined each time (Table 7). As expected, there is a decrease in total sediment yield by increased vegetation in the stream channels (Fig. 10). Nevertheless, this decrease is relative small as compare with the previous analysis: 10–15% reduction on sediment yield from the highest vegetation amount to the lowest one.

In the light of the simulations carried out with EUROSEM, we can state that the morphology and topography of the watersheds play a much more important role on sediment yield than the effect of vegetation on stream channels.

Table 6 – Main input values used in the simulation carried out with EUROSEM for two watersheds, for two different rainfall events

Input[a]	Unit	Channel					Plane												
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
W_T																			
Geometry																			
XL	m	196	596	583	167	328	604	978	857	625	748	853	790	150	250	797	204	797	658
W	m	0	0	0	0	0	216	132	259	105	168	423	127	45	31	224	113	252	196
S	%	0.01	0.01	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
SIR	%	0.050	0.100	0.057	0.091	0.066	0.115	0.116	0.113	0.114	0.108	0.098	0.108	0.144	0.122	0.109	0.127	0.079	0.125
ZR and ZL	–	3	4	3.2	2	4.8	0	0	0	0	0	0	0	0	0	0	0	0	0
BW	m	2	0.75	1.75	0.5	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0
W_L																			
XL	m	578	595	253	478	1025	399.3	923.7	215.7	202.3	877.2	331.9	203.5	187.8	650.5	765.4	289.8	1117.7	982.9
W	m	0	0	0	0	0	364.6	258.7	250.5	255.1	213.4	102.1	102.7	229.5	160.5	163.3	380.3	515.1	371.5
S	%	0.01	0.01	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
SIR	%	3	4	3.8	2	4.8	0	0	0	0	0	0	0	0	0	0	0	0	0
ZR and ZL	–	3	4	3.8	2	4.8	0	0	0	0	0	0	0	0	0	0	0	0	0
BW	m	2	0.75	1.75	0.5	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0
$W_T - W_L$																			
Hydrology																			
MANN	$m^{1/6}$	0.0766 (0.055–0.109)[b,c]					0.119[b,c]												
FMIN	mm/h	0.24 (0–0.59)[b] | 0.08 (0–0.21)[c]					0.44 (0.16–0.99)[b] | 1.26 (0.46–2.88)[c]												
G	mm	325 (0–812)[b,c]					754 (581–808)[b,c]												
POR	% (v/v)	0.181 (0–0.453)[b,c]					0.475[b,c]												
THI	–	0.42[b] | 0.31[c]					0.42[b] | 0.31[c]												
Erosion																			
PLANTH	cm	0[b,c]					11 (10–15)[b,c]												
EROD	g/J	1.6[b,c]					1.6[b,c]												
RFR	m/m	0[b,c]					25[b,c]												
RECS	mm	0[b,c]					125[b,c]												
COH	Kpa	1.59[b] | 1.19[c]					9.4[b] | 4.5[c]												
D_{50}	μm	150[b] | 112[c]					48.5 (43.2–54.6)[b] | 36.4 (32.4–40.9)[c]												
Vegetation																			
COVER	%	0[b,c]					0.04[b,c]												
DINT	mm	1.2 (0–3)[b,c]					3[b,c]												
SHAPE		0[b,c]					1[b,c]												
PLANGE	degree	0[b,c]					85[b,c]												
PLANTBASE	%	0[b,c]					0.01[b,c]												
Textural classes							Silty clay								Clay loam	Silty clay		Silty clay loam	

For variable values, minimum and maximum are given in parentheses.

[a] XL: channel/plane length; W: plane width; S: channel slope; SIR: average interrill slope; ZR and ZL: right and left channel slope; BW: bed width; MANN: channel/plane roughness; FMIN: saturated hydraulic conductivity; G: effective capillarity; POR: porosity; PLANTH: plant height; EROD: soil erodibility; RFR: downslope land roughness; RECS: water-level elevation over the surface; COH: soil cohesion in saturation; D_{50}: average particle size; COVER: percentage of vegetation cover; DINT: maximum water interception; SHAPE: leaf shape; PLANGE: angle between the soil surface plane and the plant stem; PLANTBASE: The percentage basal area of the vegetation cover expressed as a fraction between 0 and 1.

[b] Total rainfall: 51.65 mm.

[c] Total rainfall: 19.83.

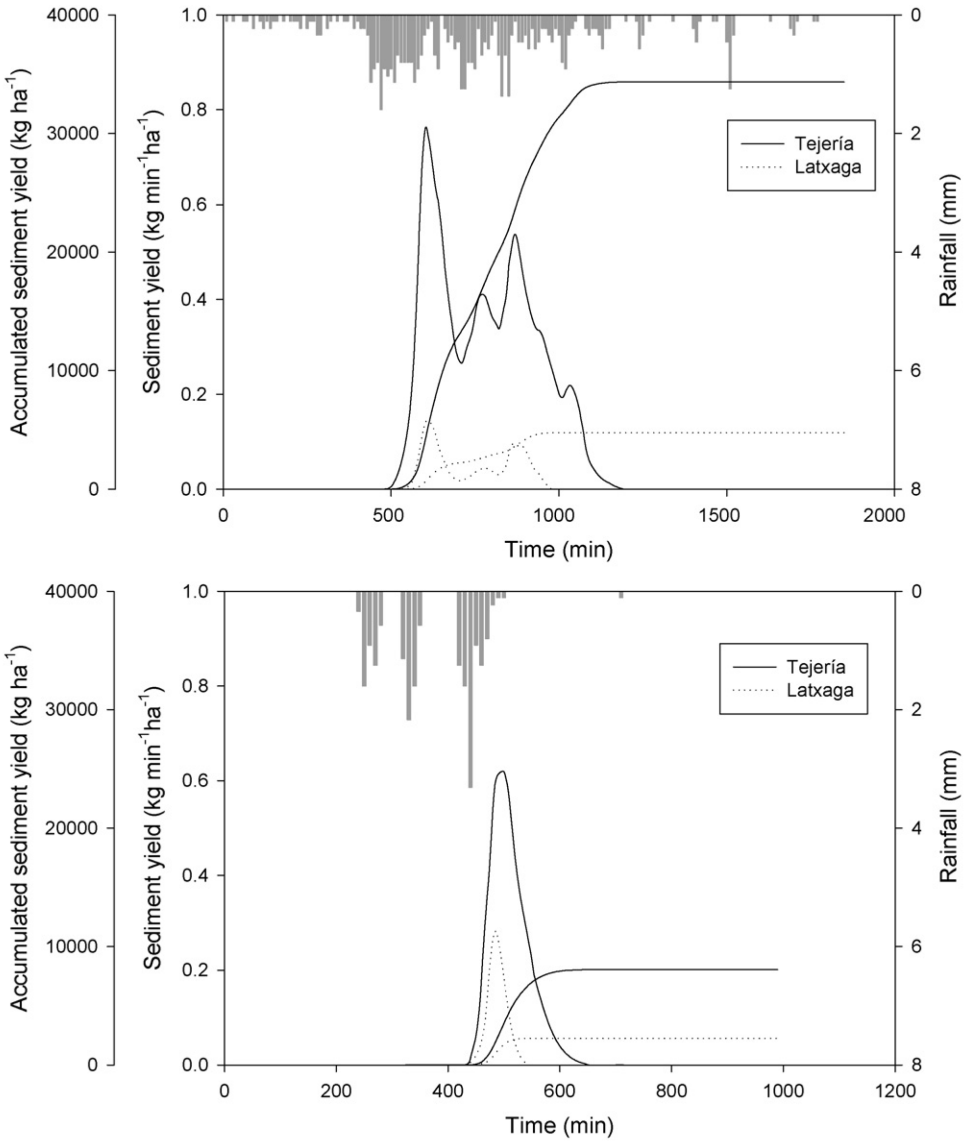

Fig. 9 – Recorded hyetograph and simulated sedigraphs of two different watersheds for two rainfall events. Full line: watershed with similar hydrological characteristics to La Tejería's (W_T). Dotted line: similar to the former one but with watershed morphology similar to Latxaga's (W_L). Up: total rain, 65 mm; time, 1860 min. Down: total rain, 19.8 mm; time, 1000 min simulation performed using EUROSEM (Morgan et al., 1998).

Additionally, La Tejería has a rather small drainage network (Table 1), which may contribute to a more frequent overland flow leading to the formation of erosion features such as ephermeral gullies or rills (Fig. 8). Precisely, and as mentioned above, no gullies/rills are present at Latxaga, which has a larger drainage network than La Tejería.

Table 7 – Range of variation of the total roughness (n_{total}) for the stream channels in La Tejería for a given n_4 value (after Arcement and Schneider, 1989)

Amount of vegetation	n_4	n_{total}
Small	0.010	0.055–0.063
Medium	0.025	0.070–0.081
Large	0.050	0.095–0.109
Very large	0.100	0.145–0.167

3.3. *Nitrate and phosphate in water courses*

The analysis of the water revealed clear differences between both watersheds in terms of nitrate concentration (Table 5, Figs. 3 and 11). At Latxaga watershed, the nitrate concentrations rarely exceeded the critical level of 50 mg NO_3 l^{-1} for drinking water (Fig. 11) (EC, 1991). Conversely, at La Tejería, nitrate concentrations were over that threshold almost the whole year (Fig. 11). This is surprising since, as mentioned above, Latxaga has received much fertilization than La Tejería. Moreover, and provided the presence of phosphorus in the water, only about 0.30 mg l^{-1} of nitrate is needed for algal

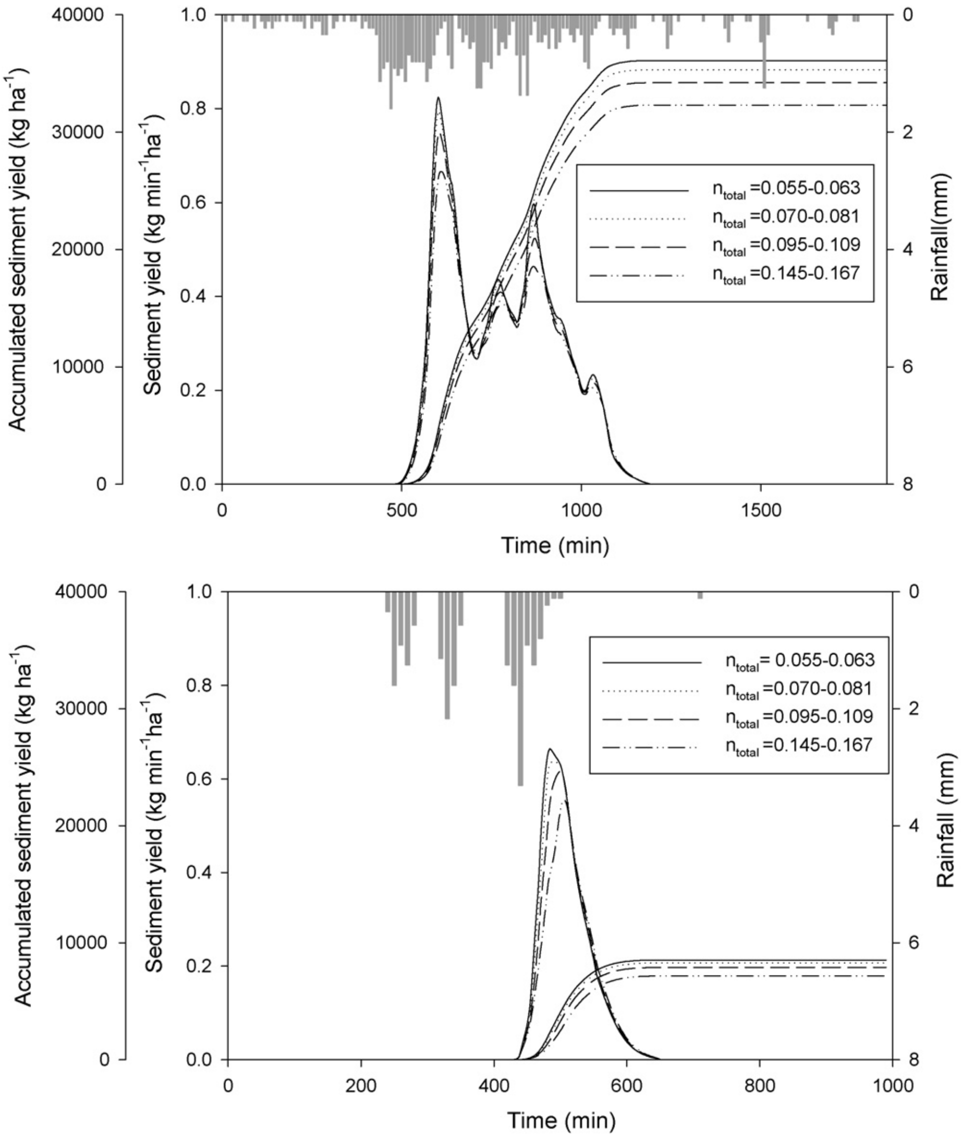

Fig. 10 – Simulated pluviographs and sedigraphs of two different rain events for La Tejería using different roughness coefficient values for vegetation and flow conditions in the stream channels (i.e., n_4, see text for details). n_{total} is Manning's *n* total (see text for details) Up: total rain, 65 mm; time, 1860 min. Down: total rain, 19.8 mm; time, 1000 min. Simulation performed using EUROSEM (Morgan et al., 1998).

blooms, i.e., eutrophication (Brooks et al., 1997): this critical level was largely surpassed in both watershed most of the time. The nitrate concentration variability was small (Fig. 11). This suggests that the main stream was fed to some extent by nitrate-loaded groundwater. Then, nitrate concentration did not appear to be as strongly affected by rainfall variability as sediment concentration (Figs. 6 and 11). Previous studies have already showed the base flow as the main source of nitrate to

Table 8 – Reference values of nitrate loads in water courses reported in the literature

Land use/management	Nitrate load (kg NO_3–N ha^{-1} year^{-1})	Reference
Pristine watersheds	0.76–2.3[a]	Howarth et al. (1996)
Mixed (49% agric., 26% for., 18% urb.)	24.21[a]	Pieterse et al. (2003)
Irrigated agriculture	59.00	Causapé et al. (2004)
Non-irrigated agriculture	26.10	Schilling and Zhang (2004)
Non-irrigated agriculture	22.46	Honisch et al. (2002)
Organic agriculture (4 years old)	10.85	Honisch et al. (2002)

[a] Correspond to total nitrogen load.

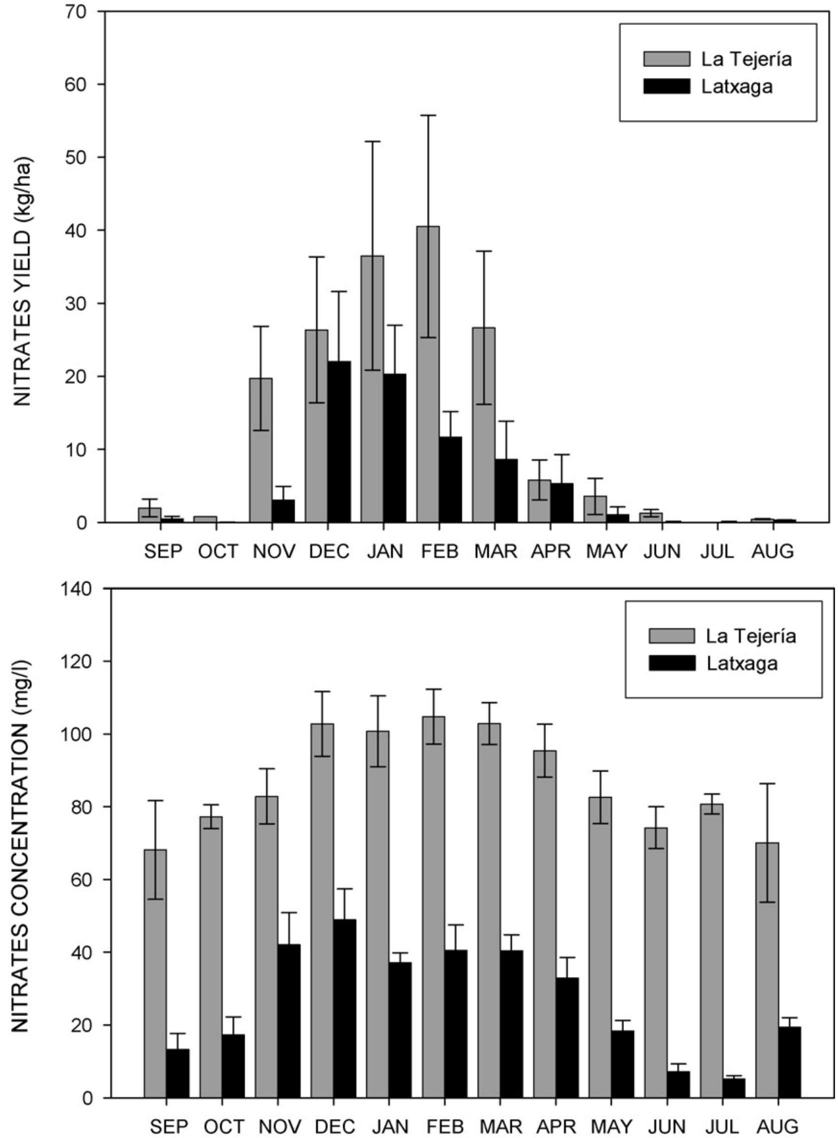

Fig. 11 – Monthly average nitrate yields and concentrations at La Tejería and Latxaga.

the surface water bodies (Hyer et al., 2001; Schilling and Zhang, 2004; Angier et al., 2005). Additionally, nitrate concentration showed a clear seasonal pattern in both watersheds with the highest concentrations occurring during the winter and early spring months (Fig. 11). As regards average nitrate yield, there were also important differences between both watersheds (Table 5, Fig. 11). The average exported nitrate yield at La Tejería was double that recorded at Latxaga (Table 5), with important variability in both cases (Fig. 11). Average nitrate yield at Latxaga and La Tejería are higher than others reported on non-irrigated agriculture lands (Table 8). Moreover, at both watersheds, nitrate yields were considerably higher than those recorded in pristine watersheds and organic agricultural lands (Table 8). Considering the efficiency on fertilization practices, the estimated nitrate losses represent on average 22% of the total amount applied with fertilization at La Tejería and 8% at Latxaga, with maximum losses of 34% (on 2002–2003) at La Tejería, and 12% (on 2003–2004) at Latxaga. Some authors have reported even higher nitrate losses (30–80%) in intensive winter barley growing areas of Spain (Angás et al., 2006).

With regard to phosphate, similar concentrations were recorded in both watersheds (Fig. 12). Yet, phosphate concentrations were also higher at La Tejería than at Latxaga (Table 5). Both values corresponded to water with a significant eutrophication risk (EEA, 1999). Unlike nitrate concentration, a great variability was observed in phosphate concentration (Fig. 12): this was much affected by rainfall-runoff events. Therefore, phosphate seems to travel preferentially with direct runoff as occurs with sediments (Hyer et al., 2001; Angier et al., 2005). Besides, no clear seasonal pattern of the phosphate concentration was evidenced in either of the watersheds (Fig. 12). Average phosphate yields were much similar in both watershed (Table 5, Figs. 3 and 12). Differences on nitrate and phosphate concentration and yield may account to some extent for distinction in morphology, and

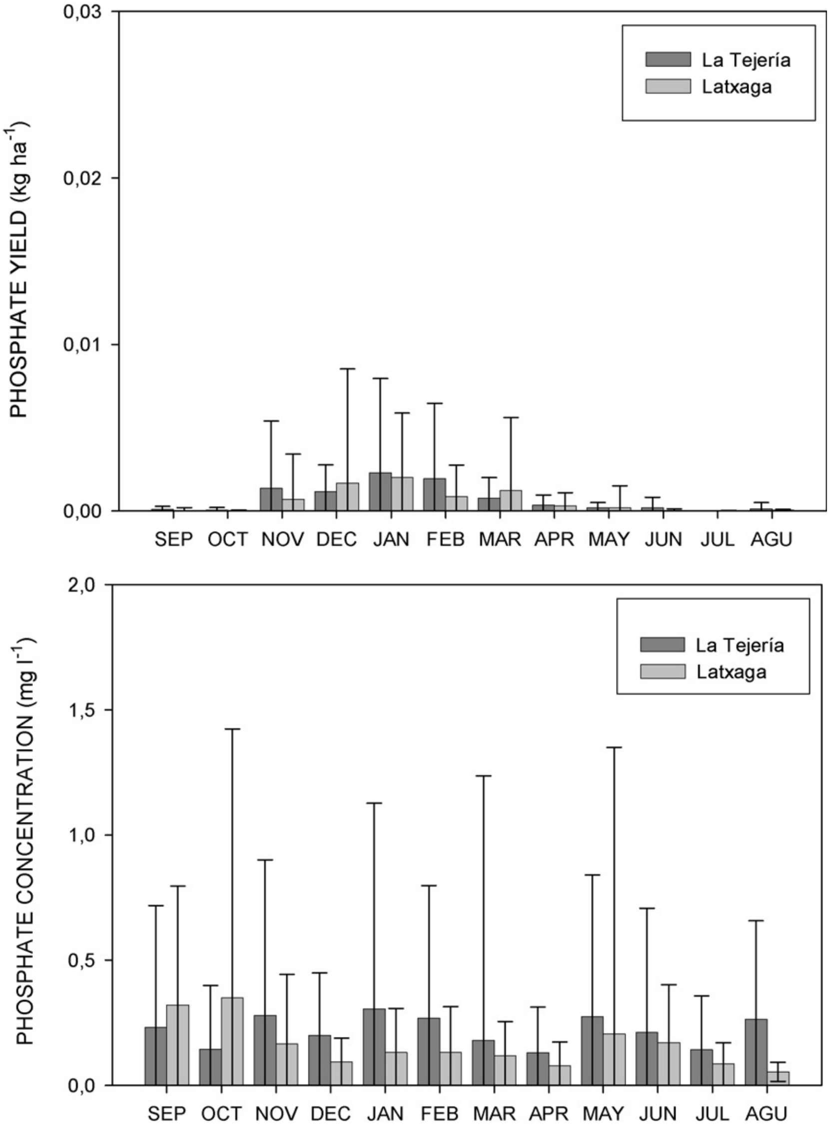

Fig. 12 – Monthly average phosphate yields and concentrations at La Tejería and Latxaga.

riparian and stream channel vegetation patterns between both watersheds. While at Latxaga the drainage network is denser and stream channels are densely vegetated, at La Tejería the drainage density is lower, the stream channels are kept bare and the tillage operations mostly reach the stream banks. The benefits of riparian buffers and vegetation strips on stream water quality improvement have been intensively observed and analyzed (Klapproth and Johnson, 2000; Broadmeadow and Niesbet, 2004; Fiener and Auerswald, 2006). The data recorded at our experimental watersheds seem to corroborate these previous studies and highlight the importance of vegetation strips for maintaining acceptable water quality conditions in the watercourses of agricultural lands.

4. Conclusions

In an unprecedented study for Navarre (Spain), two experimental agricultural watersheds (namely La Tejería and Latxaga) belonging to the agricultural experimental watershed network of the Government of Navarre, have been monitored for several years and their hydrological and water quality data analyzed. Both watersheds can be considered as being representative for wide areas of Navarre and Spain as regards their morphology, climate and management.

An important inter-annual (and also intra-watershed spatial) variability of sediment and pollutant yields was observed, which is in agreement with the current climatic characteristics. This study reveals the existence of natural streams with unacceptable concentrations (for human consumption and for the environment) of nitrates and phosphates in representative agricultural areas apparently not affected by any significant pollution, and also the occurrence of high erosion rates. Only few rainfall events largely accounted for exported sediment and nutrient rate in both watersheds. Nevertheless, sediment yield was more related to current soil conditions than to the erosive capacity of the rains.

Our findings also show clear differences in the behaviour of both watersheds, especially in terms of sediment and nitrate concentration and yield. Those differences have been, *a priori*, unexpected because both watersheds are close to each other and their soils, land use and management practices are also similar. However, some differences mainly in watershed morphology and topography as well as vegetation on stream channels largely accounted for the observed discrepancy between both sites.

The dataset collected at these sites is of great relevance for research on topics related to hydrology, erosion and water quality issues. Nevertheless, further investigation in this issue is clearly warranted, even at larger spatial and temporal scales considering the high variability of the phenomena involved.

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