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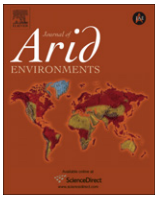

# A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain

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## ABSTRACT

Climate, lithology, soil and especially, intense land use/cover changes, make SE Spain very vulnerable to runoff generation and water erosion leading to loss of nutrients and organic matter and to infrequent but devastating floods, reservoir siltation and mass failures. This susceptibility has led to heavy economic investment and research efforts since the 1980s, making this region a worldwide reference for understanding the hydrology and geomorphology of semiarid ecosystems. Runoff and soil erosion have been intensively studied throughout the last decades in various natural ecosystems as well as in abandoned farmlands. Research has considered a wide range of methods and spatial and temporal scales. This paper reviews the methods and data describing runoff generation and water erosion, synthesising the key processes involved, rates, thresholds and controlling factors from a scale-dependent perspective. It also identifies the major gaps in current knowledge to provide recommendations for further research towards solutions that reduce the negative impacts of erosion. Research in SE Spain has contributed significantly to a better understanding of the effect of spatial and temporal scale on runoff and sediment yield measurements, and highlighted the important role of distinct erosion and sediment transport processes, hydrologic connectivity, spatial and temporal patterns of rainfall, the occurrence of extreme events and the impacts of land use changes. The most effective ways and challenges to predict runoff, soil erosion and sediment yield at the catchment scale are also discussed.

## 1. Introduction

The most important changes that soils have undergone during the past two centuries are the consequence of human communities which have accelerated soil erosion rates and rerouted nutrient flows (McNeill and Winiwarter, 2004). Such human impacts have been very intense in south-eastern Spain, a region with a long history of human settlement where anthropogenic land use changes have been especially drastic in the second half of the past century (Burke and Thornes, 2004), triggering soil erosion and leading to severe land degradation. These land use changes, along with its climate, with scarce and torrential rainfalls, steep slopes and the fragility of its soil (low levels of organic matter, aggregate stability and nutrients) make this region very prone to surface sealing, runoff generation and water erosion (García-Ruiz, 2010). This in turn leads to soil and nutrient loss, soil organic matter decline and infrequent but devastating floods, reservoir siltation and mass failures (Burke and Thornes, 2004). In this framework, soil erosion, by itself and also in its overriding role in desertification, has become a matter of public concern since the 1980s in SE Spain, and intense research has been done in the context of EU research projects (e.g. MEDALUS (Mediterranean Desertification and Use) I, II and III, MEDACTION, PESERA, RECONDES etc) and others supported by regional or national funds (e.g. LUCDEME: Fighting against Desertification in the Mediterranean). Heavy economic investment and research efforts have resulted in significant progress in understanding the hydrology and geomorphology of semiarid ecosystems, making the region a worldwide reference for soil erosion and hydrological research in semiarid environments. Most research has been done in natural ecosystems and recently abandoned farmlands (since about the 1960s) on which this review is focused, though, in SE Spain today, the main actual water erosion problems are associated with abandonment of agriculture and marginal farmlands on marls and steep, stony

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hillslopes, in olive and almond orchards and vineyards (Romero-Díaz, 2002; Solé-Benet, 2006).

This paper reviews the main studies carried out in semiarid south-eastern Spain with the purpose of: i) providing an overview of the key factors and processes influencing runoff generation and water erosion processes in semiarid environments from patch to catchment scale; ii) examining achievements and main challenges in runoff and erosion prediction, and iii) identifying major gaps in knowledge and recommending further research oriented towards the mitigation of soil erosion and its negative impacts.

## 2. Geographical framework

South-eastern Spain is structurally part of the Betic Cordillera, a mountain system formed as a result of complex interactions of the African and Iberia Plates during the Alpine orogeny, still tectonically active (Weijermars, 1991). The lithology of the area is diverse, from Paleozoic high-grade metamorphic rocks (mica schists, quartzites, and marble) to Neogene soft sedimentary rocks (marls and clays infilling most depressions between mountain ranges). Intermediate lithological types include low-grade metamorphic rocks (e.g. slates), and hard sedimentary rocks like sandstones and limestones. The complex and intense tectonics of this region has provided a wealth of ores in many of its mountain ranges, and since ancient times, mining activities have produced intense but localised land degradation in the mountains, which were still forested until the middle of the 18th century. By the beginning of the 20th century deforestation was almost complete. In the first decade of the 20th century, soil conservation activities were started by Spanish government and some successful reaforestation such as in the Sierra Espuña (Murcia) is reported.

The region's semiarid Mediterranean climate ($P = 200–600$ mm, with recurrent intensities over 30 mm $h^{-1}$), is characterized by summer droughts and local, convectional storms in autumn producing high runoff rates and intense soil erosion.

The generally steep topographic gradients on hillslopes and the drainage networks which are far from equilibrium can produce high rates of runoff, erosion and sedimentation. Intermountain basins, subsident during the Neogene, have been filled with soft sedimentary rocks, like marls, mudstones or shales, and uplifted during the Quaternary (Weijermars, 1991). As a consequence, the drainage network is in different phases of incision and coupling (Harvey, 2002) and the differential uplifts have contributed to several changes in river systems, including captures and new equilibriums in hillslope to channel connectivity. In this context of soft rock dissection, badlands become relevant in the geomorphology of SE Spain, extending through most of the valleys and developed on a variety of materials with a wide range of morphologies and processes. Wide differences in rainfall infiltration and erosion rates (Calvo-Cases et al., 1991) can be found within and between different badlands areas, depending on the lithology and other local factors. Material properties also play a relevant role in the development of pipe systems that contribute to the rapid development of gullies and badlands (Romero Díaz at al., 2007; Faulkner et al., 2008).

The lithological variety results in a considerable diversity of soils, though the climate determines their overall dryness, generally low organic matter content and weak soil structure. Shallowness and low water-holding capacity contribute to a generally sparse plant cover which also provides very little protection against erosive agents, especially since the massive deforestation in the 18th and 19th centuries. The upper and steeper parts of most mountain ranges are now covered by Leptosols, with Calcisols and Regosols in their footslopes and Fluvisols in the main drainage ways.

Besides the physical aspects just described, the human geography is also an essential part of this territory. Traditionally, most land has been used as pasture, for dryland farming, and for irrigated agriculture only along ephemeral river valleys in favourable years. In the last 50 years the migration of population to coastal areas, with rapid expansion of tourism-related activities, abandonment of dryland agriculture, and intensification of both grazing and irrigation, have all resulted in many changes in land use and cover, causing new degradation processes like groundwater overexploitation and pollution, enhanced runoff due to sealed surfaces (Martín Rosales et al., 2007) and extreme land levelling. In some areas, abandonment has affected over 70% of farmland (Douglas et al., 1996) resulting in soil erosion increase. In Murcia, abandonment affected 100,000 ha (9.1% of the total surface) of farmland since 1980, although with positive consequences in many cases, e.g. rapid shrub colonization and increased soil organic matter, being the bedrock a key factor controlling the rapidity of plant colonization or soil erosion after farmland abandonment (Romero Díaz, 2003).

## 3. Monitoring runoff and soil erosion in SE Spain: an overview

A wide variety of soil erosion measurement methods has been applied in SE Spain covering a wide range of spatial and temporal scales (see Romero Díaz, 2002 and Boix-Fayos et al., 2005). Methods used to monitor runoff and soil erosion included (i) *direct field measurements* at different spatial scales, including different forms and types of erosion plots, morphological transects, erosion pins and profilemeters, quantifications with Caesium 137, rainfall simulation experiments, experimental catchments and bathymetrical surveys of reservoirs, and (ii) *indirect methods*, which include modelling (see Section 5), remote sensing and GIS analysis, and estimation with topographic benchmarks related to vegetation, dendrochronology and DEM reconstruction.

The highly heterogeneous results derived from different monitoring and measuring methods are related mainly to: (i) the spatial and temporal scale of measurements; (ii) the disturbance and inadequate representation of natural conditions (continuity, connectivity and heterogeneity of natural systems), and (iii) the complex ecosystem interactions (Boix-Fayos et al., 2006). All these issues overlap in several aspects but the concepts of spatial and temporal scales and thresholds are basic to all of them. Cammeraat (2002) and de Vente and Poesen (2005) explain and exemplify how processes are related across scales and which water erosion processes are dominant at different spatial scales, respectively. In addition, important thresholds in rainfall parameters can be identified. For example, plot scale threshold conditions for erosive rainfalls were established at 10–15 mm $h^{-1}$ in 30 min in Murcia (Martínez-Mena et al., 2001), 8.4 mm $h^{-1}$ at 10 min interval in Alicante (Calvo-Cases et al., 2005), 4.2 mm $h^{-1}$ at 10 min interval in Murcia (Cammeraat, 2002), and 5.6 mm $h^{-1}$ at 5 min interval in Tabernas (Almería) (Cantón et al., 2001).

Specific examples from SE Spain of data variability due to methodological aspects of runoff and erosion measurement are given by Boix-Fayos et al. (2007a) concerning: (i) Differences in long-term soil erosion data between open and closed plots; (ii) Differences in soil loss derived from replica soil erosion plots and (iii) Differences in soil loss data derived from plots at a range of spatial scale.

Because the acquisition of representative soil loss data is a very complex issue, data derived must be interpreted according to the spatial and temporal scale of acquisition and their own methodological constraints. Very often experimental data cannot be extrapolated to larger or other areas, due to all of the above, but

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are indicative for comparing treatments or driving forces. It is important to keep in mind the specific purposes of the study for the design of suitable methods to measure the hydrological response and erosion rates, and caution should be exercised in comparing measurements based on different methodologies, temporal or spatial scales.

## 4. Controls, mechanisms and rates at different spatial and temporal scales

Research in SE Spain has demonstrated that factors controlling movement of water and sediment vary according to a range of spatial scales, but are related across scales, and the connections are complex (e.g. Cammeraat, 2002; Puigdefábregas et al., 1999; Calvo-Cases et al., 2003; de Vente and Poesen, 2005). Furthermore, the evolution of the system and subsequent hydrological and erosion response is highly dependent on the interactions and feedback-dominated processes at patch and hillslope scales (Cammeraat, 2002; Puigdefábregas, 2005; Boix-Fayos et al., 2006). The following paragraphs discuss the main factors and processes controlling runoff and erosion for distinct scales. Yet, throughout, we stress the fact that processes at one spatial or temporal scale interact with processes at another scale, and the results of such cross-scale interactions often have nonlinear dynamics.

### *4.1. Patch scale*

The SE Spain landscape is spatially structured forming a mosaic of sources and sinks of water, sediments and nutrients where runoff and erosion show strong spatial variability. The presence or absence of vegetation is considered the main factor determining the hydrological and erosion response at patch scale and its influence results from complex processes that act on different time scales. In the short term, the canopy modifies the volume and intensity of rainfall reaching the soil surface and affects the detachment and entrainment of sediment in overland flow. In the long term, plants improve soil beneath them (Puigdefábregas et al., 1999) and contribute to its differentiation from the surrounding inter-plant areas, a feature which in turn has strong implications for water and sediment redistribution (Puigdefábregas, 2005).

It is widely accepted that runoff and sediment yield diminish (linearly or exponentially) with increasing plant cover, from a certain threshold of cover (Francis and Thornes, 1990; Quinton et al., 1997). However, this relationship can vary greatly depending on the plant architecture (Quinton et al., 1997), stage of plant development, the adaptation of canopy density to available water resources and the stage of succession, especially after land abandonment (Cammeraat et al., 2005). Moreover, the relationship can reverse, and runoff and erosion sometimes increase with increasing vegetation cover as consequence of hydrophobicity of the organic litter on soil below bushes for the case of runoff (Puigdefábregas et al., 1999; Contreras et al., 2008) or due to sediment exhaustion in patches with little vegetation cover (Nicolau et al., 1996). Variation in the plant root system can impact at least as much as vegetation cover on rill and ephemeral gully erosion (De Baets et al., 2007).

Even more accentuated is the variability of runoff and erosion rates in open areas (Fig. 1) where surface soil properties (e.g. stone cover, crust cover, surface roughness) regulate runoff and erosion (Calvo-Cases et al., 2003; Arnau-Rosalén et al., 2008). Physical and biological soil crusts have an important role in runoff and erosion (see Maestre et al., in this issue). In general, both types of crusts act as sources of runoff (Calvo-Cases et al., 1991; Cantón et al., 2001, 2002; Mayor et al., 2009), however, biological soil crust, unlike physical crusts, stabilize soils and reduce soil erosion (Fig. 1). The influence of stone cover is highly variable (Fig. 1) due to their ambivalent effect on infiltration depending on position, size and cover (Poesen et al., 1998). Stones positioned on the soil surface generally prevent soil from sealing and reduce runoff and erosion. However, stones embedded in the soil surface, contribute to the establishment of a continuous crust which promotes runoff.

Other critical conditions affecting runoff generation and erosion at the finest temporal and spatial scales are rainfall intensity (Cantón et al., 2002; Cammeraat, 2004) and antecedent soil water content (Gomez-Plaza et al., 2001; Cantón et al., 2001). Variation in both determines soil surface morphologies and exerts a major control on runoff and sediment yield (Cerdà, 1999), and also affects

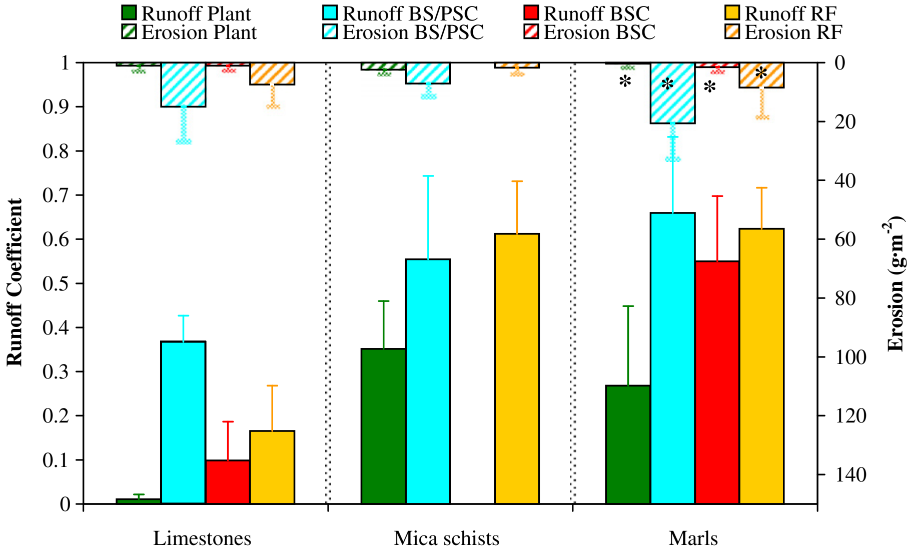

**Fig. 1.** Runoff coefficient and erosion rates obtained with rainfall simulations (1 h duration and a constant rainfall intensity of about 55mmh$^{-1}$) on 0.25 m$^2$ size closed plots on three different lithologies: limestones (Benidorm, Alicante), Mica schist (Rambla Honda, Almeria) and Marls (Tabernas, Almería). The differences among plant covered patches and the most frequent different types of covers appearing in open areas: bare soil (BS) or physical soil crust (PSC); biological soil crusts (BSC) and rock fragments (RF) are shown. In all cases average values from at least four plots are represented, and the selected plots were always covered with at least 80% of each correspondent surface component. * indicates that means and standard deviations values are divided by 20. Data come from rainfall experiments partially published in Calvo-Cases et al. (1991) and Solé-Benet et al. (1997) for Tabernas; Nicolau et al. (1996) for Rambla Honda and Boix-Fayos (1999) for Benidorm.

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fine-scale hydrological connectivity (Bracken and Croke, 2007). Erosion processes active in inter-rill areas comprise splash and flow detachment, and transport by overland flow and deposition of soil particles (Calvo-Cases et al., 2003).

Open patches act as a source of water, sediments and nutrients that are trapped by vegetated patches, acting as sinks. This lessens connectivity of runoff pathways and only during exceptionally high rainfalls sinks become saturated and contribute to runoff and promote connectivity. Puigdefábregas (2005) states that the spatial structure of water and sediment sources and sinks is not static, but evolves dynamically with hillslope fluxes regulating their spatial configurations to them.

### 4.2. Hillslope and microcatchment scale

#### 4.2.1. Factors, processes and rates of water and sediment movement on hillslopes

Relevant factors at the patch scale, such as the presence of vegetation, crusts, stones or rock outcrops, are organized at a higher spatial level (hillslopes) and their spatial patterns are a key factor conditioning the response of hillslopes to the generation of runoff and the transfer of water and sediments.

Different controlling factors and erosion processes interact, and different water and sediment sinks and sources appear from patch to catchment scale. In general, selective erosion or low energy processes (i.e. surface wash) take place at fine scales (i.e. hillslope) and non-selective erosion processes (i.e. gullying) progressively appear with larger observation scales up to a certain threshold after which selective processes for deposition become dominant. Although erosion studies in SE Spain have documented soil loss rates since the 1980s, detailed studies have continued incorporating a larger variety of factors (natural versus agricultural ecosystems, different land uses, land use changes and management techniques, different plant and stone covers and crusts) and coarser measurement scales. At the hillslope scale, where more process combinations occur and at microcatchment scale a wide variety of erosion rates (Table 1) have been documented during the last decade. Apart from the reasons exposed in Section 3, values seem very dependent on scale and environment/process.

Much hillslope-scale soil erosion research in SE Spain in the last five years has concentrated on the effect of land use and management techniques on runoff and soil erosion (van Wesemael et al., 2006; Martínez-Mena et al., 2008; Cerdà et al., 2009). Recent research is also interested in new methods to provide a more accurate hillslope-scale measurements on longer time scales, such as topographic benchmarks related to vegetation (Vanwalleghem et al., 2010), dendrochronology, DEM reconstruction (Lesschen et al., 2008), and hillslope connectivity issues (Arnau-Rosalén et al., 2008; Lesschen et al., 2009; Meerkerk et al., 2009).

**Table 1**
Recent erosion values recorded at different scales and from different erosion processes.

| Environment | | Rates | Units | References |
|---|---|---|---|---|
| Hillslope scale | Interrill | 0.02–0.11 | t ha$^{-1}$ yr$^{-1}$ | Bautista et al., 2007 |
| | | 0.33–2.35 | | Martínez-Mena et al., 2008 |
| | | 0.04–0.38 | | Cantón et al., 2009 |
| | Rills | 87 | mm yr$^{-1}$ | Solé-Benet et al., 2010 |
| | Gullies | 29–105 | t ha$^{-1}$ yr$^{-1}$ | Romero Díaz et al., 2010 |
| | | 87 | | Lesschen et al., 2009 |
| | | 0.56–28.92 | t ha$^{-1}$ event$^{-1}$ | Cantón et al., 2001 |
| | Piping | 287 | t ha$^{-1}$ yr$^{-1}$ | Romero Díaz et al., 2010 |
| | Tillage erosion | 26.6 | | van Wesemael et al., 2006 |
| Microcatchment scale | | 0.85–2.99 | | Martínez-Mena et al., 2001 |
| | | 0.1–4.5 | | Cantón et al., 2001 |

#### 4.2.2. Hillslope-channel coupling and connectivity

Concepts of runoff generation and transfer of water and sediments that better fit the hydrological behaviour of Mediterranean slopes and their coupling with channels have been redefined in the last decade. A mixed runoff generation model combining Hortonian runoff and saturation flow (mainly on topsoil) with reinfiltration areas at the hillslope scale, causing flow discontinuity has been described in several studies in SE Spain (Cammeraat, 2002; Calvo-Cases et al., 2003, 2005; Meerkerk et al., 2009). A step further was taken by Bracken and Croke (2007) reviewing the concept of hydrological connectivity which provides a basis for integrating processes of runoff generation with landscape characteristics. The connectivity concept describes interconnection between morphological landscape components, by which the material fluxes move across and through the drainage basin. Thus, connectivity is applied to the transfer of water and sediment from one part of the landscape to another. Several attempts to quantify connectivity include Bracken and Croke's (2007) "Volume to Breakthrough" index, the "Flowlength" (Mayor et al., 2008) and catchment scale models by Reaney (2008).

Runoff and sediment connectivity are not always linked, as on resistant substrates like limestone and on biological soil crusts which can also lead to high runoff rates but low soil loss rates (Cantón et al., 2002). Non-selective erosion processes play a major role in the transfer of sediments from hillslopes to channels, both by connecting morphological segments and incorporating large amounts of sediments into the channels. Hooke (2003) developed a field identification method for slope-channel connections, and identified erosion in gullies and banks as the main slope-to-channel sediment source. This was also observed by Boix-Fayos et al. (2007b) in the Region of Murcia. Along with rill networks, (ephemeral) gullies have also been pointed out as major sediment sources in other areas, transferring large volumes of sediment downslope. When ephemeral gullies become permanent, they increase landscape connectivity by coupling hillslopes directly with the river-channel system. In contrast to the increase in connectivity by channels, hillslope deposits and sedimentary fans on footslopes reduce system connectivity dramatically (Faulkner et al., 2008).

Other process affecting hillslope connectivity is the construction of new terraces with heavy machinery for reforestation which has triggered water erosion in Murcia (Romero Díaz et al., 2010), Almería and Granada (Martín-Rosales et al., 2007).

### 4.3. Catchment scale

Catchment runoff and sediment yield depend on a wide range of variables and reflect the combined effect of all active and interacting runoff, erosion and sediment deposition processes as well as the time over which measurements take place (de Vente and Poesen, 2005).

Scale dependency in runoff and erosion is considered an important issue and several studies higher rainfall thresholds for runoff generation at coarse scales than at fine scales, supporting the decreasing relation between area-specific runoff yield with increasing area (Puigdefábregas et al., 1999; Cammeraat, 2002; Boix-Fayos et al., 2006). In small areas, this decrease is mainly related to variability in infiltration, spatial distribution of vegetation and soil surface properties, and local patchiness within Hydrologically Similar Surfaces (HYSS) (Kirkby et al., 2002) as described above. In large watersheds, scale dependency of runoff is also attributed to other factors, such as storm cell size, spatial differences in lithology and channel width, catchment morphometry (slope length and morphology), increasing storage possibilities in the valley domain (Kirkby et al., 2002, 2005; Bracken and Croke, 2007; Lesschen et al., 2009).

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Fig. 2 shows the relationship between catchment area (A) and mean annual sediment yield (SY) for a total of 61 Spanish catchments, based on published reservoir sedimentation measurements (Avendaño Salas et al., 1997). This graph shows that although there is wide variation, on average, SY decreases with increasing A. SY in south-eastern Spain is slightly higher (average 4.43 t ha$^{-1}$ yr$^{-1}$), but not significantly different, from SY in the other Spanish catchments (average 4.22 t ha$^{-1}$ yr$^{-1}$), and the overall trend is in agreement with often reported decreasing SY with increasing A (de Vente et al., 2007). More striking is that catchment SY is generally significantly higher than average erosion rates measured in plot studies (de Vente and Poesen, 2005; de Vente et al., 2008). Extensive reviews of erosion plot studies in the Mediterranean and in SE Spain have shown that these typically average around 1.0–1.5 t ha$^{-1}$ yr$^{-1}$ (Boix-Fayos et al., 2005). From this, it can be inferred that gully and bank erosion and mass movements form an important part of the catchment sediment budget in these environments. This is further confirmed by modelling, field measurement and tracer studies demonstrating a significant contribution ($>$80%) to SY from gully erosion, bank erosion and mass wasting (de Vente et al., 2008).

The predominance of an erosion or sediment transport process depends on the spatial scale, topographic thresholds, rainfall magnitude-frequency-duration characteristics, initial soil moisture content, and soil biological activity (Cammeraat, 2002), and is also influenced by the spatial configuration of land use, land cover, topography and lithology (de Vente et al., 2007). For small spatial units on hillslopes, SY can either increase or decrease due to discontinuity of overland flow in landscapes with patchy vegetation or highly variable soil surface conditions (Cammeraat, 2002; Calvo-Cases et al., 2003; Boix-Fayos et al., 2006; Arnau-Rosalén et al., 2008). However, above certain thresholds, when rill erosion, gully erosion, bank erosion and mass movements are initiated, connectivity and SY generally increase with increasing A, until slope gradient decreases, SY becomes transport-limited and decreases with further increasing A (de Vente and Poesen, 2005).

Among the rainfall characteristics, storm duration, rainfall intensity and temporal variability appear as key features determining catchment runoff (Kirkby et al., 2005; Reaney et al., 2007; Bracken et al., 2008). Bracken et al. (2008) found floods to be more closely related to the total rainfall occurring in a spell of rain than to the intensity of a storm, although intense bursts of rain control the nature and timing of the flood hydrograph. Reaney et al. (2007) used a runoff production simulation model for semiarid areas to demonstrate that the temporal fragmentation of high-intensity rainfall is crucial in determining the distances overland flow travels, and thus the amount of runoff that leaves the slope as discharge. Moreover, spatial distribution of rainfall (i.e. where the storm happens in the catchment and its movement direction) has important hydrological consequences, especially with torrential rains.

The time scale of observation is another important factor related to the interval of recurrence of extreme rainfall events, to the occurrence of ‘sediment waves’ through a catchment (Puigdefábregas et al., 1999; Cammeraat, 2004), and to the delayed or absent response of SY to conservation measures or changing land use that may reduce some erosion processes but induce others (Boix-Fayos et al., 2007b). The importance of (historic) low-frequency catastrophic floods for discharge, channel dynamics and sediment transfer is emphasised by various authors (see Machado et al. in this issue). All these examples show how the arbitrary choice of spatial and temporal measurement scale significantly affects results.

At catchment scale, the important effects of land use/cover changes as a result of the relocation of people to the coastal border, forest fires, the abandonment of farms and grazing land, the rapid expansion of tourism-related activities, and the intensification of agriculture, among others are also well documented in SE Spain. García-Ruíz (2010) shows how some land use changes in mountain areas (from forest to pasture and from pasture to farmland) greatly enhance erosion. However, conversion of matorral (shrubland and dry grassland communities) to Pinus forest in Alicante had no influence in runoff and erosion rates though it reduced species richness and plant diversity in the understorey of the plantations (Chirino et al., 2006). Mayor et al. (2007) report the effects of forest fires on catchment scale for seven years, indicating that during the

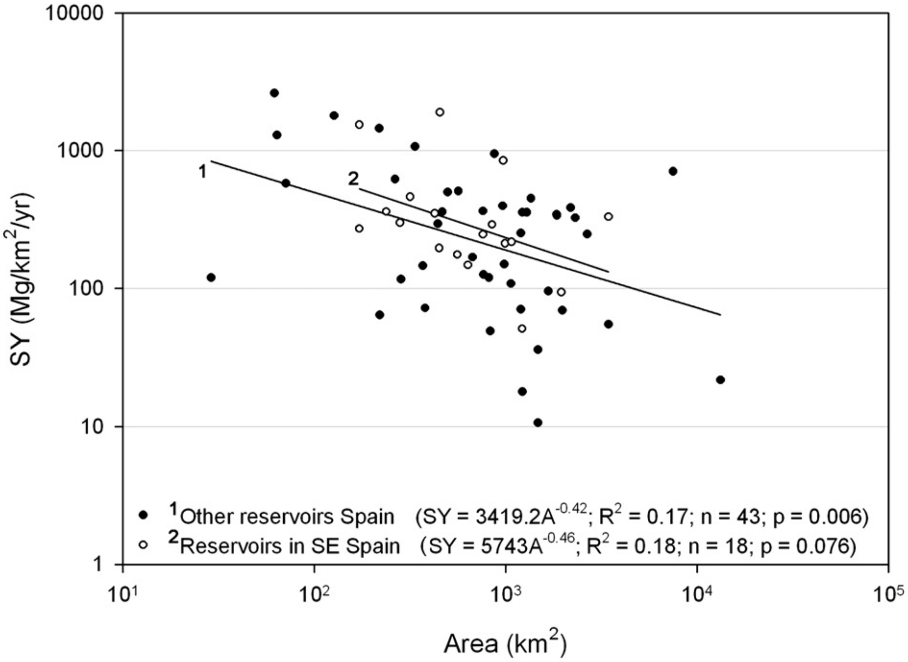

**Fig. 2.** Relation between catchment area (A) and sediment yield (SY) for catchments from SE Spain compared to other Spanish catchments.

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first year, runoff was three orders of magnitude higher, and SY over four orders of magnitude higher in the burned catchment than in the unburned catchment, though such differences decreased progressively with time.

## 5. Modelling runoff and erosion

A wide range of models have been applied to predict runoff, soil erosion and sediment yield under current and possible future land use and climate conditions. There are two general reasons for modelling: 1) prediction of on-site erosion or regional sediment yield, runoff generation and flood occurrence, and 2) simulation to increase process understanding of runoff generation, soil erosion and sediment transport and their relationships with environmental characteristics (e.g. slope, soil, land cover, climate). A table is included in the appendix showing an overview of models applied in SE Spain representing the main model types (i.e. process based, empirical, factorial, regression) and their purpose (i.e. prediction or simulation).

Wide differences are observed between model predictions and field measurements. With estimated local erosion rates well over 50 t $ha^{-1}$ $yr^{-1}$, models based on the Universal Soil Loss Equation (RUSLE) usually strongly overestimate soil loss rates compared to field measurements in plot studies or even compared to sediment yield observed in reservoirs (Boix-Fayos et al., 2005; de Vente et al., 2008). These high erosion predictions in SE Spain can partly be explained by the frequent occurrence of a high rock fragment cover, especially on steep slopes, usually not accounted for in soil erodibility assessments. For example, a rock fragment cover of 50% may cause an overestimation of soil loss of around 80% (Poesen et al., 1998). High gross erosion rates were also obtained with the WATEM-SEDEM model that combines the RUSLE with a sediment transport component, whereas relatively good estimates were obtained for predicted catchment sediment yield with this model (de Vente et al., 2009). On the other hand, soil loss assessments with the PESERA model showed good agreement with soil loss rates measured in plot studies, but not with reservoir sedimentation rates (de Vente et al., 2008). This was explained by the fact that permanent gully erosion, bank erosion and mass movements are not included in the model equations (de Vente et al., 2008). In contrast, relatively good results were obtained with scoring models like FSM, PSIAC and SPADS for prediction of sediment yield since these models specifically account for gully and bank erosion processes, although with the limitation that these models do not provide a quantitative indication of source areas or gross erosion rates (de Vente et al., 2008). Only two models were applied for the whole of SE Spain, as part of national or pan-European assessments: PESERA and the (R)USLE (ICONA, 1988; van der Knijff et al., 2000; Kirkby et al., 2008).

Various simulation studies demonstrated the importance of hydrological and sediment connectivity as affected by vegetation patterns, terrace removal or failure, changing soil surface, vegetation cover and rainfall conditions (Kirkby et al., 2002, 2005; Lesschen et al., 2009; Meerkerk et al., 2009). Sinks in the form of terraces or densely vegetated spots strongly reduce sediment yield (Lesschen et al., 2009). Consequently, the widely observed decrease in intact terraces in south-eastern Spain has led to a strong increase in connectivity and discharge (Meerkerk et al., 2009).

An important finding supported by modelling studies is that the dynamics of runoff producing areas vary over time as a function of rainstorm conditions (Kirkby et al., 2002, 2005). Moreover, it was demonstrated that antecedent soil moisture conditions strongly affect the runoff response during medium and low-intensity storms, but hardly affect peak discharge during high-intensity rainstorms (Castillo et al., 2003).

The importance of interacting erosion and sediment deposition processes combined with the spatial and temporal scale dependency of sediment yield makes their prediction and interpretation by modelling at the catchment scale extremely complicated. Modelling runoff, erosion and sediment transport at the catchment scale in semiarid environments is especially complicated due to: 1) high spatial variability of surface conditions (i.e. soil, soil cover), 2) high spatial and temporal variability of rainfall events, 3) the importance of low-frequency, high-magnitude events for sediment detachment and transport, 4) the importance of gully erosion, bank erosion and mass movements for the sediment budget. Furthermore, the nature of stream-slope coupling in semiarid areas is substantially different from humid environments (Kirkby et al., 2002; Bracken and Croke, 2007), which to a large extent is explained by discontinuous runoff on hillslopes, the complex interaction between different erosion and sediment transport processes and the great importance of extreme rainfall events for detachment and transport of sediments across scales (Puigdefábregas et al., 1999; Cammeraat, 2004).

## 6. Identification of major needs for research

The main issues that require more attention in the near future are:

1. Building on previous research, multi-scale studies to facilitate spatial upscaling of runoff and erosion rates and provide data on the spatial connections between different units at each scale are necessary. Long-term data series are still scarce, and deriving reliable information on average erosion rates at several spatial scales is difficult. Data are also needed on thresholds for medium to severe erosion to initiate and for irreversible situations of land degradation and to define feedback loops to reverse soil degradation driven by soil erosion.
2. At fine scales (patch and hillslope), aspects like the relative importance of different soil surface components (e.g. rock fragment and crust cover, surface roughness, soil depth and soil organic carbon content) and their interactions in driving the hydrological behaviour of open areas remains unclear (Mayor et al., 2009). Greater effort should be made in this direction and should include the influence of types of crusts and their stage of development, roughness and vegetation types.
3. Further research is needed on thresholds for connectivity of water and sediment flows at all scales and the role of streams as sediment sources and (temporal) sinks. It is poorly understood how hillslope inputs along stream networks are linked to catchment-scale response. Research is often conducted along a specific plot/stream reach or at a single catchment scale and the transferability of results to other catchments or the development of general principles is limited (Jencso et al., 2009). One particular gap in knowledge deals with factors influencing connectivity dynamics (Bracken and Croke, 2007) such as the relationship between storm input and connectivity or the influence of the temporal fragmentation of high-intensity rainfalls in determining the overland flow travel distances and the amount of runoff leaving the slope as discharge (Reaney et al., 2007).
4. Despite the important advances that remote sensing data have provided in monitoring the spatial variability of soil cover and surface characteristics and for upscaling, some aspects need more attention: the detection of erosion features like gullies, piping or medium-sized rills, the accurate assessment of senescent vegetation cover, changes in the state of vegetation in large catchments and monitoring of dryland channel changes

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which are highly complex because of their low-frequency functioning and highly dynamic nature (Hooke, 2007).

5. Some erosion processes deserve more attention in future model development. Although field data clearly demonstrate its importance, most catchment-scale modelling studies have disregarded the contribution of gully erosion, bank erosion and mass movements to the sediment budget (de Vente et al., 2008). Piping has also been observed in both natural and anthropogenic landscapes, in different lithologies and under different types of land-use and vegetation cover in SE Spain (Romero Díaz et al., 2007). However, the complete understanding of the involved mechanisms, the interaction of environmental factors controlling the development of pipe networks and collapse and thresholds as well as the influence of piping on catchments response and modelling need to be particularly considered. Moreover, when sufficiently detailed and high-quality input data are available, hydrological model performance will increase when the dynamics of some parameters like hydraulic resistance, saturated hydraulic conductivity, soil structure changes, and soil crusting are considered, all of which are dynamic during rainfall events (Jetten and Favis-Mortlock, 2006).
6. Climate and land use changes affect runoff and erosion at local and regional scales. Studies considering a variety of scenarios of land use in the context of a changing climate can assist in interpreting the enormous complexity of catchment responses observed, and can be very valuable for the development of sustainable land management systems. Furthermore, the risks and hazards for unsustainable land uses must be evaluated, and soil and water conservation practices should be tested through experimental research at various scales. Moreover, to ensure effective implementation and acceptance by stakeholders, a well designed participation framework for knowledge exchange and consensus building is crucial (Schwilch et al., 2009).
7. Around the Mediterranean, heavy investments are continuously being made in reforestation projects and the construction of check-dams in gullies and streams, to reduce the negative impacts of erosion, such as flooding and sedimentation of reservoirs. There is also a long history of European and national subsidies designed to promote certain land use changes or land management practices to prevent soil erosion and maintain water resources and fertile soils. While the effects of different conservation measures is widely studied in experimental plots, only a very few studies have evaluated the biophysical and socioeconomic implications and effectiveness of such conservation measures at catchment or regional scale (Boix-Fayos et al., 2007b; Romero Díaz et al., 2010). Given its importance for sustained food production and controlling on-site and off-site damage from erosion, these issues require more attention in future studies.

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## Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jaridenv.2011.03.004.

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