

Factors controlling sediment yield at the catchment scale in NW Mediterranean geoecosystems

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Abstract

Purpose This study aimed to (1) increase understanding of the relation between sediment yield and environmental variables at the catchment scale; (2) test and validate existing and newly developed regression equations for prediction of sediment yield; and (3) identify how better predictions may be obtained. **Materials and methods** A correlation and regression analysis was performed between sediment yield and over 40 environmental variables for 61 Spanish catchments. Variables were selected based on availability and expected relation with diverse soil erosion and sediment transport processes. For comparison, the Area Relief Temperature (ART) sediment delivery model was applied to the same catchments. Sediment yield estimates obtained from reservoir surveys were used for model calibration and validation. **Results and discussion** Catchment area, catchment perimeter, stream length, relief ratio, Modified Fournier Index, the RUSLE's R factor, and catchments percentage with poor vegetation cover showed highest correlations with sediment

yield. Stepwise linear regression revealed that variables representing *topography, climate, vegetation, lithology, and soil characteristics* are required for the best prediction equation. Although calibration results were relatively good, validation showed that the models were unstable and not suitable for extrapolation to other catchments. Reasons for this unstable model performance include (1) lack of detail and quality of the data sources; (2) large variation in catchment characteristics; (3) insufficient representation of all relevant erosion and sediment transport processes; and (4) the presence of nonlinear relations between sediment yield and environmental variables. The nonlinear ART model performed relatively well but systematically overpredicted sediment yield. A model reflecting human impacts, including dams and conservation measures, is expected to provide better results. This, however, requires significantly more input data. **Conclusions** Although important insight is obtained into the relation between sediment yield and environmental factors, prediction of sediment yield at the catchment scale requires alternative approaches. More detailed information is required on land cover (change), and the effect of soil conservation measures. Validation of regression equations is a necessity, and better predictions are obtained by nonlinear models.

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1 Introduction

Understanding and predicting sediment yield from catchments form an essential part of geomorphologic and ecosystem research, and are indispensable to support policy decisions dealing with off-site effects of soil erosion such as

sediment deposition within river channels and reservoirs, flooding, coastal development, and contamination of floodplains and water bodies with agrochemicals and other pollutants associated with the eroded sediments (Clark 1985; Owens et al. 2005; Ramos and Martinez-Casasnovas 2004; Steegen et al. 2001; Syvitski and Milliman 2007; Verstraeten and Poesen 1999; WCD 2000; Woodward 1995). Moreover, river sediment fluxes play an important role in various natural geochemical cycles, such as the carbon cycle (Ludwig and Probst 1998; Ludwig et al. 1996). Before predictions of sediment yield can be made, understanding the integrated effect of diverse erosion and sediment transport processes in relation to land use and climate change is needed. In recent decades, significant progress has been made in the development of spatially distributed, process-based soil erosion models such as LISEM (de Roo 1998; de Roo et al. 1996), EUROSEM (Morgan et al. 1998), WEPP (Flanagan et al. 1995; Foster et al. 1995), LAPSUS (Schoorl and Veldkamp 2001) and PESERA (Kirkby et al. 2004). However, mainly because of the large data requirements and difficulty of describing the effects of all relevant erosion and sediment transport processes, operational application of these models at the catchment scale is often problematic. A first step towards understanding and prediction of sediment yield at the catchment scale, therefore, is the use of lumped regression equations (e.g. Achite and Touaibia 2000; Ali and de Boer 2008; Dendy and Bolton 1976; Grauso et al. 2008; Hadley et al. 1985; Langbein and Schumm 1958; Lixian et al. 1996; Ludwig and Probst 1998; Ludwig et al. 1996; Restrepo et al. 2006; Syvitski et al. 2005; Tamene et al. 2006; Verstraeten and Poesen 2001). In these equations, sediment yield is often related to catchment characteristics in terms of morphology, topography, lithology, climate, discharge and soil properties. Obviously, these regression relations not only serve prediction purposes but also provide insight into relations between catchment characteristics and sediment yield that can be used for the further development of more complex models.

Table 1 provides some examples of regression equations as reported in the literature for the prediction of sediment yield for various regions worldwide. An extensive overview and discussion of regression equations can be found in Ludwig and Probst (1998) and in Jansson (1982), who grouped equations according to drainage basin size and climatic conditions. The equations in Table 1 illustrate the range of variables used in regression studies. Some equations are based on only one variable, but most use several variables to predict sediment yield. The variables most often reported to be related to sediment yield can be grouped as *topography* (e.g. relief ratio, slope), *climate* (e.g. mean annual rainfall, erosivity index), *soil and lithology* (e.g. % of soil texture class or erodible lithology),

hydrology (e.g. mean or maximum runoff discharge), *vegetation cover* or *land use* (e.g. % forest or orchards), *drainage network* (e.g. drainage density, stream length), and *catchment morphology* (e.g. basin area, form factor). Beside the variety in variables, it is interesting to observe the large differences in optimal prediction equations for sediment yield in different parts of the world. These differences highlight that (1) erosion and sediment transport processes depend on many interacting environmental factors; (2) a factor that is important in one area can be insignificant in another; and so (3) no straightforward globally effective relations are apparent, and hence region-specific relations are needed for predicting sediment yield.

The objective of this study is to assess the relation between sediment yield at the catchment scale and data on topography, climate, land use, catchment morphology, drainage network, lithology and soil properties, for NW Mediterranean geoecosystems, using 61 Spanish study catchments. Furthermore, the aim is to test to what extent these regional data can be used in a multiple linear regression model for the prediction of sediment yield. This study follows on from a previous study where the sediment yields of 22 Spanish catchments were related to environmental factors of climate, topography and land use (Verstraeten et al. 2003). In the latter study, it was observed that, although a relatively good regression equation was obtained ($R^2=0.80$), the model was very unstable since exclusion of outliers changed the model and greatly reduced the model performance ($R^2=0.29$). As explanation for the model instability, it was concluded that land cover information lacked detail, and that the process of gully erosion was not sufficiently represented by included variables. Therefore, beside a higher resolution for most data, in this present study, more factors that potentially can be a proxy for the occurrence of gully and bank erosion (e.g., lithology, drainage density) were included in the analysis, and the dataset was extended to 61 catchments for which measured sediment yield data were available from the literature. In addition to the first two objectives—for comparison and to test the potential of a global prediction equation as an alternative to regionally calibrated equations—the Area Relief Temperature (ART) sediment delivery model that was developed for assessment of sediment load of global rivers (Syvitski et al. 2003; Syvitski et al. 2005) was also applied to and validated for the 61 Spanish catchments.

2 Materials and methods

2.1 Sediment yield data of Spain

Sediment yield was calculated from published sedimentation rates in 61 reservoirs in Spain (Avendaño Salas et al.

Table 1 Examples of published regression relations for the prediction of sediment yield

| Location | Regression model | R ² | N | Reference |
|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|-----|-------------------------------------------|
| Algeria | SSY = 26.62*LI + 5.07*PI + 9.77*Tor - 593.56 | 0.92 | 30 | Demmak (1984) |
| Belgium | SSY = 25*A ^{-0.4} (with area in ha) | 0.64 | 26 | Verstraeten and Poessen (2001) |
| | SY = 25*A ^{0.6} (with area in ha) | 0.80 | 26 | |
| | ln SSY = 3.72 - 0.72*ln A - 0.84*ln HI + 0.11*ln SL (with area in ha) | 0.76 | 26 | |
| | ln SSY = 0.21*L + 22.2*HD - 988*HI (with area in ha and L in m) | 0.92 | 26 | |
| China | ln SSY = -2.65 + 0.96*S + 0.002*L ² + 8.41*L ^{0.5} - 4.16*L ^{2/3} + 3.22*W ^{0.5} - 1.45*W ^{2/3} - 2.23*T + 2.46*T ² - 1.36*For ² | 0.63 | 200 | Lixian et al. (1996) |
| Colombia | log SSY = -0.88 + 0.81*log Q - 0.39*log Q _{max} | 0.58 | 32 | Restrepo et al. (2006) |
| Ethiopia | SY = 690*TDL - 0.58*SWC | 0.96 | 11 | Haregeweyn et al. (2005) |
| | SSY = 0.86*S - 0.269*SWC + 10 | 0.80 | 11 | |
| Ethiopia | log SSY = 2.33 + 0.007*GulB + 0.003*EL + 0.002*RG - 0.007*Bush | 0.96 | 11 | Tamene et al. (2006) |
| Italy | SSY = 497.61 - 1.74*A + 129.42*E - 12.61*S - 0.29*MAP + 121.18*DD | 0.82 | 42 | Bazzoffi et al. (1997) |
| Maghreb | ln SSY = 4.79 + (54*10 ⁻³ *K) + (4*10 ⁻³ *R) - (5.6*10 ⁻⁵ *A) | 0.71 | 36 | Probst and Amiotte-Suchet (1992) |
| Romania | log SY = 4.50 - 0.18*log O + 0.75*log A + 0.04*log FF + 0.10*log DD + 0.33*log RR + 0.54*log MAP | 0.74 | 63 | Ichim (1990) |
| Romania | log SY = 7.99 + 0.81*log A - 0.30*log BR + 0.15*log DD - 0.15*log RR + 0.09*log For - 1.57*log MAP | 0.92 | 36 | Ichim (1990) |
| South-Africa | SSY = 1.45*P - 0.78 | 0.78 | 15 | Roberts (1973) |
| Spain | SSY = 20.6*RR + 18*D - 14*For - 33*Foma - 31*Orch - 173*PV | 0.80 | 22 | Verstraeten et al. (2003) |
| USA | SSY = 1280*Q ^{0.46} *(1.43 - 0.26*log A); for Q < 2 in./year | 0.75 | 505 | Dendy and Bolton (1976) |
| | SSY = 1958e ^{-0.055Q} *(1.43 - 0.26*log A); for Q > 2 in./year (with SSY in t/mi ² , Q in inches, and A in mi ²) | | | |
| USA | SSY = 0.39*DD + 1.85; with DD based on permanent and ephemeral streams | 0.02 | 17 | Allen (1986) |
| | SSY = 2.81*DD + 1.81; with DD based on permanent streams | 0.08 | 17 | |
| | SSY = 0.75 + DD - 0.16; with DD based on aerial photos | 0.83 | 17 | |
| USA | log(SSY + 100) = 6.21 - 2.19*log(PT + 100) + 0.06*log(S + 100) - 0.02*log(CS + 100) + 0.04*log(AI + 100) (with SSY in acre feet per square mile) | 0.92 | 39 | Flaxman (1972) |
| Global | ln SSY = -0.416*ln A + 4.26*10 ⁻⁴ *H _{max} + 0.15*T _m + 0.095*T _{range} + 0.0015*R + 3.585 | 0.49 | 86 | Hovius (1998) |
| Global | Qs = 2*10 ⁻⁵ *A ^{0.50} *HD ^{1.50} *e ^{0.1*T_m} (for Polar regions, T _m < 0°C) | 0.76 | 48 | ART model: Syvitski et al. (2003) |
| | Qs = 6.1*10 ⁻⁵ *A ^{0.55} *HD ^{1.12} *e ^{0.07*T_m} (for temperate regions with latitude > 30°N) | 0.63 | 162 | |
| | Qs = 0.31*A ^{0.40} *HD ^{0.66} *e ^{-0.1*T_m} (for tropical regions, 0-30°N) | 0.58 | 62 | |
| | Qs = 0.57*A ^{0.50} *HD ^{0.37} *e ^{-0.1*T_m} (for tropical regions, 0-30°S) | 0.67 | 42 | |
| | Qs = 1.3*10 ⁻³ *A ^{0.43} *HD ^{0.96} (for temperate regions with latitude > 30°S) | 0.54 | 26 | |
| Global | Qs = 0.02*B*Q ^{0.31} *A ^{0.5} *R*T _m ; for T _m > 2°C | 0.96 | 488 | BQART model: Syvitski and Milliman (2007) |
| | Qs = 0.04*B*Q ^{0.31} *A ^{0.5} *R; for T _m < 2°C | | | |
| Global | SSY = 0.020*(R*Sr*Four) | 0.91 | 58 | Ludwig and Probst (1998) |

Table 1 (continued)

| Location | Regression model | R ² | N | Reference |
|----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|----|-----------------|
| Global | SSY = 6.14*p ² /MAP - 49.78; (low relief, p ² /MAP ≤ 20) SSY = 27.12*p ² /MAP - 475.4; (low relief, p ² /MAP > 20) SSY = 52.49*p ² /MAP - 513.2; (high relief, MAP > 600) SSY = 91.78*p ² /MAP - 737.62; (high relief, 200 < MAP < 600) | | 78 | Fournier (1960) |

R² correlation coefficient, N number of observations, A catchment area (km²), AI aggregation index, B factor representing glacial erosion, lithology and reservoir or lake trapping efficiency, BR bifurcation ratio, Bush % bush/shrub cover, CS % soil particles coarser than 1 mm, D distance between valley outlet and highest point at the divide (km), DD drainage density (km km⁻²), E erodible surface area (km²), EL % with erodible lithology, FF catchment form factor (-), Foma % transition forest Matorral, For % forest cover, Four Fournier Index (mm), GuIB index for gully and bank erosion (-), H_{max} maximum elevation (m), HI hypsometric integral, HD difference between highest and lowest point (m), K soil erodibility factor, L valley length (km), LI Lithology Index, LR length ratio, P LR/BR, MAP mean annual precipitation (mm), O catchment order, Orch % orchards, p maximum mean monthly precipitation (mm), PI precipitation erosivity index, PT precipitation temperature ratio (mm/°C), PVI % poorly vegetated, Q mean annual runoff (m³ s⁻¹), Qa mean annual discharge (km³ a⁻¹), Q_{max} mean maximum river discharge (m³ s⁻¹), Qs long-term sediment load (kg s⁻¹), R specific runoff (mm a⁻¹), RG index of ruggedness (km⁻¹), RR relief ratio (m km⁻²), S average slope gradient (%), Sr average slope gradient (radian), SL total stream length (m), SSY area-specific sediment yield (t km⁻² a⁻¹), SWC % of catchment treated with soil and water conservation measures, SY absolute sediment yield (t a⁻¹), T % area with terraces, T_{range} annual temperature range (°C), T_m mean annual temperature (°C), TDL total drainage length (km), Tor Tormentality Index, W average catchment width (km)

1997a, b). Volumes of sediments retained in the reservoirs were measured by the Centro de Estudios Hidrográficos (CEH-CEDEX) of the Spanish Ministry of the Environment using bathymetric reservoir surveys. The methodology was extensively described in various reports (Avendaño Salas and Cobo Rayán 1997; Avendaño Salas et al. 1995; CEDEX 1992). At the moment of the survey, the reservoirs were operative between 20 and just over 100 years. Surveys were performed between 1977 and 1994. The reservoirs are located in diverse climatic, geologic and geomorphologic regions of the country (Fig. 1), but without representation of the relatively humid northwestern area. Almost half of all catchments are semiarid with an aridity index (UNEP 1997) below 0.5. Around 82% of the catchments have an aridity index between 0.29 and 0.65 and are thus considered to be semiarid to dry subhumid. The remaining catchments are humid-subhumid to humid. The measured total sediment yield (SY) varies between ~3.5 and 5,300 × 10³ t a⁻¹, and the area-specific sediment yield (SSY) varies between 10 and 2,600 t km⁻² a⁻¹. The average surface area draining to the reservoirs is about 1,251 km².

2.2 Quantitative catchment properties and correlations

An extensive database of quantitative variables was prepared for each of the 61 catchments (Table 2). The selection of variables included in the analysis was based on the availability of the data for all 61 catchments. Furthermore, it was intended to include variables that are most widely reported to be related to soil erosion and sediment transport processes characterising topography, climate, land use, catchment morphology, drainage network, lithology and soil properties. The variables related to catchment morphology, drainage network and topography were extracted from the Shuttle Radar Topography Mission (SRTM) 3 arc-second Digital Elevation Model (DEM) distributed by the USGS EROS data centre (<http://seamless.usgs.gov/>; Rabus et al. 2003), using IDRISI software (Eastman 2003). This DEM was mosaiced and resampled to 100-m spatial resolution by bilinear interpolation. Beside the calculation of catchment area, slope gradient, minimum and maximum elevation, the DEM was used to extract a river network for all catchments by assuming a channel when the upslope contributing area is larger than 0.2 km². This threshold roughly corresponds with the river network and drainage density indicated on topographical maps at a scale of 1:50,000. One of the reasons for the use of drainage density as an explanatory factor is that it may be a proxy for gully presence. Since no numbers or maps were available on gully density for all catchments, it was decided to extract the river network as detailed as possible based on the SRTM DEM, in the hope that this drainage density would also be representative for gully density. The threshold of 0.2 km² provided the most detailed

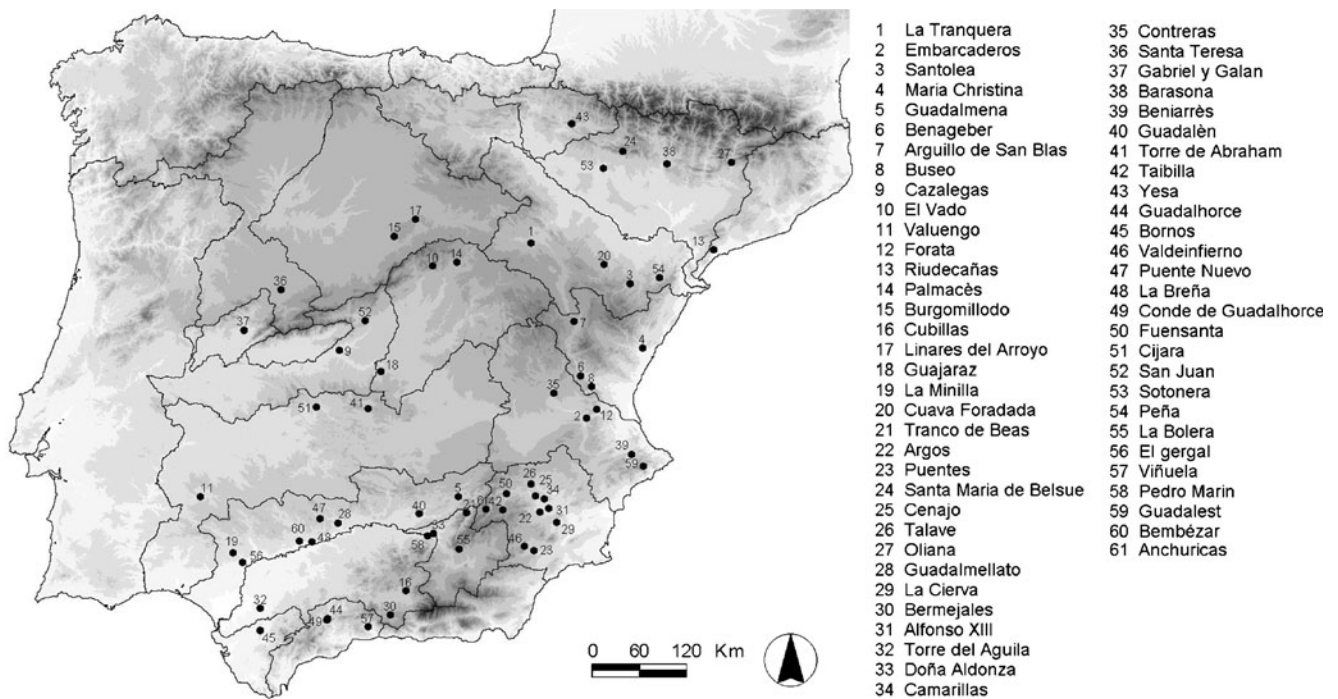


Fig. 1 Location of the 61 reservoirs in Spain

reasonable drainage network without deformations of the drainage network. For calculation of the climate variables, gridded (1 km) mean monthly rainfall and air temperature data, based on station data of the Spanish National Meteorological Institute (INM) for the period 1971–2000, were used. Mean annual precipitation for the catchments varies between 350 and 1,400 mm, and the mean annual temperature varies between 8°C and 18°C. The Precipitation Concentration Index (PCI; Oliver 1980), the Modified Fournier Index (MF; Arnoldus 1977), and the rainfall erosivity R factor (Rf; Renard and Freimund 1994) from the Revised Universal Soil Loss Equation were calculated as:

$$PCI = \frac{\sum_{i=1}^{12} p_i^2}{P^2} * 100 \quad (1)$$

$$MF = \frac{\sum_{i=1}^{12} p_i^2}{P} \quad (2)$$

$$Rf = 0.7397 * MF^{1.847}, \text{ for } MF < 55 \text{ mm} \quad (3)$$

$$Rf = 95.77 - 6.081 * MF + 0.4770 * MF^2, \text{ for } MF > 55 \text{ mm} \quad (4)$$

Here, p_i is the average monthly precipitation (millimetre), and P is the average annual precipitation (millimetre). Land

use information was extracted from the CORINE Land Cover map (CLC2000) of the European Environment Agency (EEA 2000). The CORINE map has a resolution of 100 m, and contains 44 land cover classes of which the classes that were considered most relevant for erosion prediction were selected. The variables related to lithology, soil texture and soil type were extracted from the European Soil Geographical Database at 1-km resolution (ESB 2004). This database (ESDBv2 Raster Archive) is freely available from the website of the European Soil Bureau (<http://eussoils.jrc.it/>).

2.3 Statistical analysis and model validation

A correlation analysis was performed to obtain insight into the explanatory value of individual variables for prediction of sediment yield and to identify the relation between the explanatory variables. Then, in order to find a predictive model of sediment yield, a stepwise linear regression analysis was performed with SAS statistical software (SAS 1999), using only those variables with a relatively high correlation coefficient from the correlation matrix. The stepwise regression combines forward and backward selection using a significance level threshold of 0.15. Since model development for absolute sediment yield (SY; $t \text{ a}^{-1}$) or specific sediment yield (SSY; $t \text{ km}^{-2} \text{ a}^{-1}$) provides different results (de Vente et al. 2005, 2008), model equations were calibrated for both SY and SSY.

To compare the obtained linear regression equations with other previously developed prediction equations, we also

Table 2 Summary and source of variables used in the correlation analysis

| | Abbreviation | Description | Range | Mean | Source/Reference |
|-----------------------|----------------------------------------------------------------|-------------------------------------------------------------------------------|------------|-------|----------------------------|
| Catchment morphology | A (km ²) | Catchment area | 29–13,248 | 1,251 | SRTM DEM |
| | Peri (km) | Catchment perimeter | 31–1,188 | 249 | SRTM DEM |
| | C (–) | Circle ratio is calculated as $4\pi A/Peri^2$ | 0.10–0.41 | 0.22 | SRTM DEM |
| | D (km) | Distance between the reservoir and the highest point on the catchment divide. | 7–126 | 44 | SRTM DEM |
| | FF (–) | Form Factor, calculated as A/D^2 | 0.19–1.00 | 0.52 | SRTM DEM |
| Drainage network | SL (km) | Total stream length automatically extracted | 41–20,224 | 1,837 | SRTM DEM |
| | DD (km km ⁻²) | Drainage Density, calculated as SL/A | 1.20–2.07 | 1.44 | SRTM DEM |
| Topography | S (%) | Mean slope gradient | 7–37 | 18 | SRTM DEM |
| | H _{min} (m) | Minimum elevation | 13–935 | 458 | SRTM DEM |
| | H _{max} (m) | Maximum elevation | 516–3,135 | 1,707 | SRTM DEM |
| | HD (m) | Height Difference as: $H_{max} - H_{min}$ | 503–2,812 | 1,249 | SRTM DEM |
| | H _{mean} (m) | Mean elevation | 147–1,613 | 905 | SRTM DEM |
| | HI (–) | Hypsometric Integral, as: $(H_{mean}-H_{min})/(H_{max}-H_{min})$ | 0.18–0.55 | 0.37 | SRTM DEM |
| | RR (m km ⁻²) | Relief Ratio, calculated as: $(H_{max}-H_{min})/A$ | 0.12–20.08 | 2.97 | SRTM DEM |
| Climate | MAP (mm) | Mean Annual Precipitation | 362–1,362 | 661 | INM data 1971–2000 |
| | PCI (%) | Precipitation Concentration Index (see Eq. 1) | 8.60–11.92 | 9.94 | Michiels et al. (1992) |
| | MF (mm) | Modified Fournier index (see Eq. 2) | 34–147 | 66 | Arnoldus (1977) |
| | Rf (MJ.mm.m ⁻² .h ⁻¹ .yr ⁻¹) | RUSLE erosivity factor R (see Eqs. 3–4) | 495–10,100 | 2,097 | Renard and Freimund (1994) |
| | T _m (°C) | Mean annual temperature | 8–18 | 13 | INM data 1971–2000 |
| Land use | Urban (%) | Percentage Urban area | 0–4 | 1 | CORINE (CLC2000) |
| | Ar (%) | Percentage Arable land | 0–85 | 21 | CORINE (CLC2000) |
| | OIAIm (%) | Percentage Olive and Almond orchards | 0–37 | 7 | CORINE (CLC2000) |
| | Past (%) | Percentage Pasture | 0–31 | 7 | CORINE (CLC2000) |
| | Compl (%) | Percentage Complex cultivation patterns | 0–40 | 7 | CORINE (CLC2000) |
| | For (%) | Percentage Forest cover | 1–72 | 23 | CORINE (CLC2000) |
| | Foma (%) | Percentage transition Forest Matorral | 0–24 | 10 | CORINE (CLC2000) |
| | PV (%) | Percentage Poorly Vegetated surfaces | 0–24 | 3 | CORINE (CLC2000) |
| | Mat (%) | Percentage Matorral | 1–58 | 17 | CORINE (CLC2000) |
| Lithology | Sand (%) | Percentage clastic sedimentary rock, sandstone lithology. | 0–84 | 26 | ESB (2004) |
| | Lime (%) | Percentage limestone lithology | 0–100 | 31 | ESB (2004) |
| | Marls (%) | Percentage Marls lithology | 0–100 | 41 | ESB (2004) |
| | Plut (%) | Percentage plutonic rock lithology | 0–57 | 22 | ESB (2004) |
| | Argil (%) | Percentage argillaceous rocks/shale | 0–100 | 34 | ESB (2004) |
| | Fll (%) | Percentage fluvial clays, silts, and loam | 0–41 | 11 | ESB (2004) |
| | Meta (%) | Percentage acid metamorphic rocks | 0–77 | 23 | ESB (2004) |
| Soil texture and type | Coarse (%) | Percentage coarse soil texture | 0–86 | 25 | ESB (2004) |
| | Medium (%) | Percentage medium soil texture | 0–100 | 55 | ESB (2004) |
| | Fine (%) | Percentage fine soil texture | 2–100 | 34 | ESB (2004) |
| | Fluv (%) | Percentage of Fluvisols | 0–21 | 7 | ESB (2004) |
| | Camb (%) | Percentage of Cambisols | 1–100 | 54 | ESB (2004) |
| | Lept (%) | Percentage of Leptosols | 0–100 | 41 | ESB (2004) |
| | Rego (%) | Percentage of Regosols | 0–99 | 45 | ESB (2004) |
| | Luvi (%) | Percentage of Luvisols | 0–49 | 13 | ESB (2004) |

Also indicated are the range and mean of the measured variables

applied the Area Relief Temperature sediment delivery model (ART) that was developed for assessment of prehuman sediment load of rivers worldwide (Syvitski et al. 2003, 2005). The ART model is a nonlinear regression model that was trained on a global database of 340 rivers and consists of 5 regression equations for 5 climatic zones (see also Table 1). The ART model equations predict long-term sediment load (Q_s ; kg s^{-1}) based on catchment area (A), large-scale relief (height difference; HD), and mean annual air temperature (T_m). The ART regression equation for temperate regions at northern latitudes ($>30^\circ$) was defined by Syvitski et al. (2003) as:

$$Q_s = 6.1 \cdot 10^{-5} \cdot A^{0.55} \cdot HD^{1.12} \cdot e^{0.07 \cdot T_m} \quad (R^2 = 0.63; n = 162) \quad (5)$$

Although ART was calibrated mostly for large catchments, the model is assumed to be applicable at a global scale and was also applied to smaller catchments (Syvitski and Kettner 2007). Therefore, Eq. 5 was applied to the 61 Spanish catchments, and the predicted sediment load (Q_s ; kg s^{-1}) was converted to absolute sediment yield (SY ; t a^{-1}) by multiplication of Q_s with 31,536, and to area-specific sediment yield (SSY ; $\text{t km}^{-2} \text{ a}^{-1}$) by subsequent division with catchment area.

The prediction accuracy of all regression equations was evaluated by the proportion of explained variance (R^2), the adjusted R^2 , the Model Efficiency (ME) and the Relative Root Mean Square Error (RRMSE). The ME and RRMSE are calculated as (Nash and Sutcliffe 1970):

$$ME = 1 - \frac{\sum_{i=1}^n (O_i - Pd_i)^2}{\sum_{i=1}^n (O_i - O_{mean})^2} \quad (6)$$

$$RRMSE = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - Pd_i)^2}}{\frac{1}{n} \sum_{i=1}^n O_i} \quad (7)$$

Here, n stands for the number of observations, O_i is the observed value, Pd_i is the predicted value and O_{mean} is the mean observed value. The ME can range from $-\infty$ to 1 and represents the part of the initial variance accounted for by the model. So, the closer the ME approaches 1, the more efficient the model is. The RRMSE is independent of the units, and the smaller the RRMSE value, the more accurate the model prediction.

Validation is necessary to test the robustness of the linear regression equations and explore the potential for extrap-

lation to other datasets. This is mostly done by splitting the dataset into two parts, one for model development and one for model validation. In this case, the models were validated using the “Jackknife” procedure (Shao and Tu 1995). In this procedure, $n-1$ catchments are used for calibration of the model. This calibrated model is then used for prediction of sediment yield in the remaining catchment. This is repeated n times in order to obtain independently predicted sediment yield for each catchment. This means that 61 test models were constructed, with the same independent variables, each of which excluding one reservoir at a time, and after which the model was applied for predicting SY and SSY for the remaining reservoir. The observed sediment yield of the excluded catchment was compared to the predicted value of the corresponding test model. Model performance was evaluated by the R^2 , ME and the RRMSE.

3 Results

3.1 Correlation between catchment properties and sediment yield

Table 3 shows a correlation matrix between catchment properties and area-specific (SSY) and absolute (SY) sediment yield. The nonparametric Spearman correlation coefficient was used since practically none of the variables are normally distributed. Some of the variables have a lognormal distribution (e.g. A , SL , DD , S , RR , MAP , MF), while most of the land use, lithology and soil-related variables show a skewed distribution because of many zero values for catchments where this class does not occur. Only variables with a relatively high correlation coefficient (>0.20) and those for which a relevant relation with other variables was found are included in Table 3. Only a few variables are significantly ($\alpha=5\%$) correlated with sediment yield. The most important explanatory variables for both SY and SSY are catchment area (A), stream length (SL), relief ratio (RR), Modified Fournier Index (MF), RUSLE R factor (R_f), catchment perimeter ($Peri$) and the percentage of poorly vegetated areas (PV). The high correlation coefficients between some of the variables point towards (multi-)collinearity between some variables. For example, stream length (SL), catchment area (A) and perimeter ($Peri$) are strongly correlated, and also, the percentage of soils with a fine texture and the percentage of argillaceous rocks show a strong correlation. For comparison, correlations were also assessed based on the Pearson correlation coefficient. Although correlations were slightly different, this provided the same selection of main explanatory variables as based on the Spearman correlation coefficient.

Figure 2 illustrates some of the important correlations in scatter plots. Catchment area shows a strong negative

Table 3 Correlation matrix of a selection of catchment properties and sediment yield for 61 Spanish catchments, indicating the Spearman correlation coefficient

| | Catchment morphology | | | | Drainage network | | | | Topography | | | | Climate | | | | Landuse | | | | Lithology | | | | Soil texture and type | | | |
|-------|----------------------|--------------|-------------|--------------|------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|-------------|--------------|--------------|--------------|--------------|-------------|-------------|-------------|--------------|--------------|-------------|--------------|-----------------------|--------------|-------------|--|
| | SSY | A | Peri | C | SL | DD | S | Hmin | Hmax | HI | RR | MAP | PCI | MF | Rf | Ar | OIAIm | For | PV | Mat | Lime | Marl | Argil | Meta | Med | Fine | Fluv | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| SY | 0.58 | 0.45 | 0.47 | -0.28 | 0.45 | 0.04 | 0.01 | -0.28 | 0.22 | -0.28 | -0.37 | 0.23 | 0.20 | 0.26 | 0.28 | 0.05 | 0.26 | -0.05 | 0.35 | -0.20 | -0.11 | -0.05 | 0.21 | -0.04 | -0.07 | -0.07 | 0.40 | |
| SSY | | -0.38 | 0.22 | -0.38 | -0.38 | -0.23 | 0.37 | -0.09 | 0.02 | -0.10 | 0.41 | 0.38 | 0.32 | 0.44 | 0.44 | -0.23 | 0.01 | 0.08 | 0.29 | -0.15 | -0.10 | 0.08 | -0.05 | -0.22 | -0.22 | 0.12 | 0.06 | |
| A | | | 0.97 | -0.49 | 0.99 | 0.18 | -0.31 | -0.14 | 0.24 | -0.18 | -0.90 | -0.07 | -0.18 | -0.12 | -0.10 | 0.25 | 0.23 | -0.06 | 0.06 | -0.05 | 0.04 | -0.12 | 0.30 | 0.21 | 0.18 | -0.15 | 0.36 | |
| Peri | | | | -0.64 | 0.97 | 0.23 | -0.37 | -0.21 | 0.21 | -0.20 | -0.89 | -0.14 | -0.13 | -0.17 | -0.16 | 0.33 | 0.26 | -0.10 | 0.05 | -0.08 | 0.08 | -0.05 | 0.25 | 0.17 | 0.14 | -0.11 | 0.37 | |
| C | | | | | -0.50 | -0.15 | 0.33 | 0.32 | 0.01 | -0.01 | 0.51 | 0.34 | -0.05 | 0.33 | 0.33 | -0.40 | -0.31 | 0.09 | 0.14 | 0.10 | -0.22 | -0.13 | 0.01 | 0.05 | -0.01 | -0.06 | -0.06 | |
| SL | | | | | 0.27 | -0.36 | -0.14 | 0.22 | 0.22 | -0.22 | -0.91 | -0.09 | -0.16 | -0.13 | -0.11 | 0.28 | 0.25 | -0.10 | 0.06 | -0.06 | 0.03 | -0.10 | 0.30 | 0.18 | 0.19 | -0.14 | 0.38 | |
| DD | | | | | | -0.64 | -0.16 | -0.11 | -0.37 | -0.22 | -0.50 | -0.05 | -0.47 | -0.46 | 0.50 | 0.21 | -0.54 | -0.01 | 0.01 | -0.18 | 0.32 | -0.02 | -0.17 | 0.05 | 0.19 | 0.17 | | |
| S | | | | | | | 0.15 | 0.36 | 0.33 | 0.54 | 0.47 | -0.03 | 0.43 | 0.43 | -0.69 | -0.29 | 0.57 | 0.37 | 0.09 | 0.20 | -0.08 | -0.27 | 0.21 | -0.08 | 0.07 | -0.02 | | |
| Hmin | | | | | | | | 0.51 | 0.06 | 0.19 | 0.13 | -0.49 | -0.03 | -0.01 | -0.09 | -0.61 | 0.42 | 0.06 | -0.02 | 0.31 | -0.13 | -0.06 | 0.12 | 0.04 | -0.12 | -0.13 | | |
| Hmax | | | | | | | | | -0.29 | 0.10 | 0.26 | -0.28 | 0.14 | 0.18 | 0.01 | -0.35 | 0.32 | 0.43 | -0.08 | 0.44 | 0.09 | -0.19 | 0.19 | -0.12 | 0.13 | 0.25 | | |
| HI | | | | | | | | | | 0.09 | 0.00 | -0.19 | -0.06 | -0.08 | -0.48 | -0.18 | 0.29 | -0.22 | 0.36 | 0.11 | -0.23 | 0.02 | 0.15 | 0.21 | -0.18 | -0.32 | | |
| RR | | | | | | | | | | | 0.13 | 0.04 | 0.13 | 0.12 | -0.30 | -0.30 | 0.19 | 0.15 | 0.02 | 0.07 | 0.21 | -0.45 | -0.13 | -0.23 | 0.26 | -0.25 | | |
| MAP | | | | | | | | | | | | 0.22 | 0.94 | 0.94 | -0.47 | -0.16 | 0.28 | 0.17 | 0.07 | 0.06 | -0.33 | 0.31 | 0.02 | 0.05 | -0.24 | 0.11 | | |
| PCI | | | | | | | | | | | | | 0.49 | 0.47 | 0.02 | 0.56 | -0.35 | 0.02 | -0.01 | -0.11 | 0.02 | -0.43 | -0.24 | 0.01 | -0.07 | | | |
| MF | | | | | | | | | | | | | | 0.99 | -0.42 | 0.04 | 0.12 | 0.17 | 0.08 | 0.03 | -0.27 | 0.33 | -0.10 | -0.06 | -0.17 | 0.13 | | |
| Rf | | | | | | | | | | | | | | | -0.42 | 0.03 | 0.14 | 0.20 | 0.07 | 0.04 | -0.28 | 0.33 | -0.11 | -0.05 | -0.18 | 0.15 | | |
| Ar | | | | | | | | | | | | | | | | 0.27 | -0.50 | -0.08 | -0.16 | 0.22 | 0.44 | -0.17 | -0.12 | -0.17 | 0.31 | 0.06 | | |
| OIAIm | | | | | | | | | | | | | | | | | -0.55 | -0.05 | 0.05 | -0.09 | 0.20 | 0.02 | -0.31 | -0.25 | 0.18 | 0.09 | | |
| For | | | | | | | | | | | | | | | | | | 0.12 | -0.19 | 0.22 | -0.34 | -0.08 | 0.22 | 0.18 | -0.25 | -0.07 | | |
| PV | | | | | | | | | | | | | | | | | | | -0.16 | 0.22 | 0.02 | -0.08 | 0.21 | -0.11 | -0.01 | 0.16 | | |
| Mat | | | | | | | | | | | | | | | | | | | | -0.03 | 0.01 | 0.19 | -0.09 | 0.19 | 0.01 | -0.09 | | |
| Lime | | | | | | | | | | | | | | | | | | | | | 0.13 | -0.29 | 0.13 | -0.12 | 0.17 | -0.05 | | |
| Marl | | | | | | | | | | | | | | | | | | | | | | -0.54 | -0.15 | -0.64 | 0.91 | 0.09 | | |
| Argil | | | | | | | | | | | | | | | | | | | | | | | -0.01 | 0.43 | -0.52 | 0.00 | | |
| Meta | | | | | | | | | | | | | | | | | | | | | | | | 0.16 | -0.06 | 0.10 | | |
| Med | | | | | | | | | | | | | | | | | | | | | | | | | -0.59 | -0.15 | | |
| Fine | | | | | | | | | | | | | | | | | | | | | | | | | | 0.18 | | |

SY absolute sediment yield (t a⁻¹), SSY area-specific sediment yield (t km⁻² a⁻¹), A catchment area (km²), Peri perimeter (km), C circle ratio (-), SL stream length (km), DD drainage density (km km⁻²), S mean slope gradient (%), Hmin minimum altitude (m), Hmax maximum altitude (m), HI hypsometric integral (-), RR relief ratio (m km⁻²), MAP mean annual precipitation (mm), PCI Precipitation Concentration Index (%), MF Modified Fournier Index (mm), Rf rainfall erosivity factor (MJ mm m⁻² h⁻¹ a⁻¹), Ar percentage arable land, OIAIm percentage olive and almond orchards, For percentage forest, PV percentage poorly vegetated areas, Mat percentage Matorral, Lime percentage limestone, Marl percentage Marls, Argil percentage Argillite rock, Meta percentage of metamorphic rock, Med percentage with medium soil texture, Fine percentage with fine soil texture, Fluv percentage Fluvisols

Correlation statistics in *italic and bold* are significant at 1%; those underlined at 5%

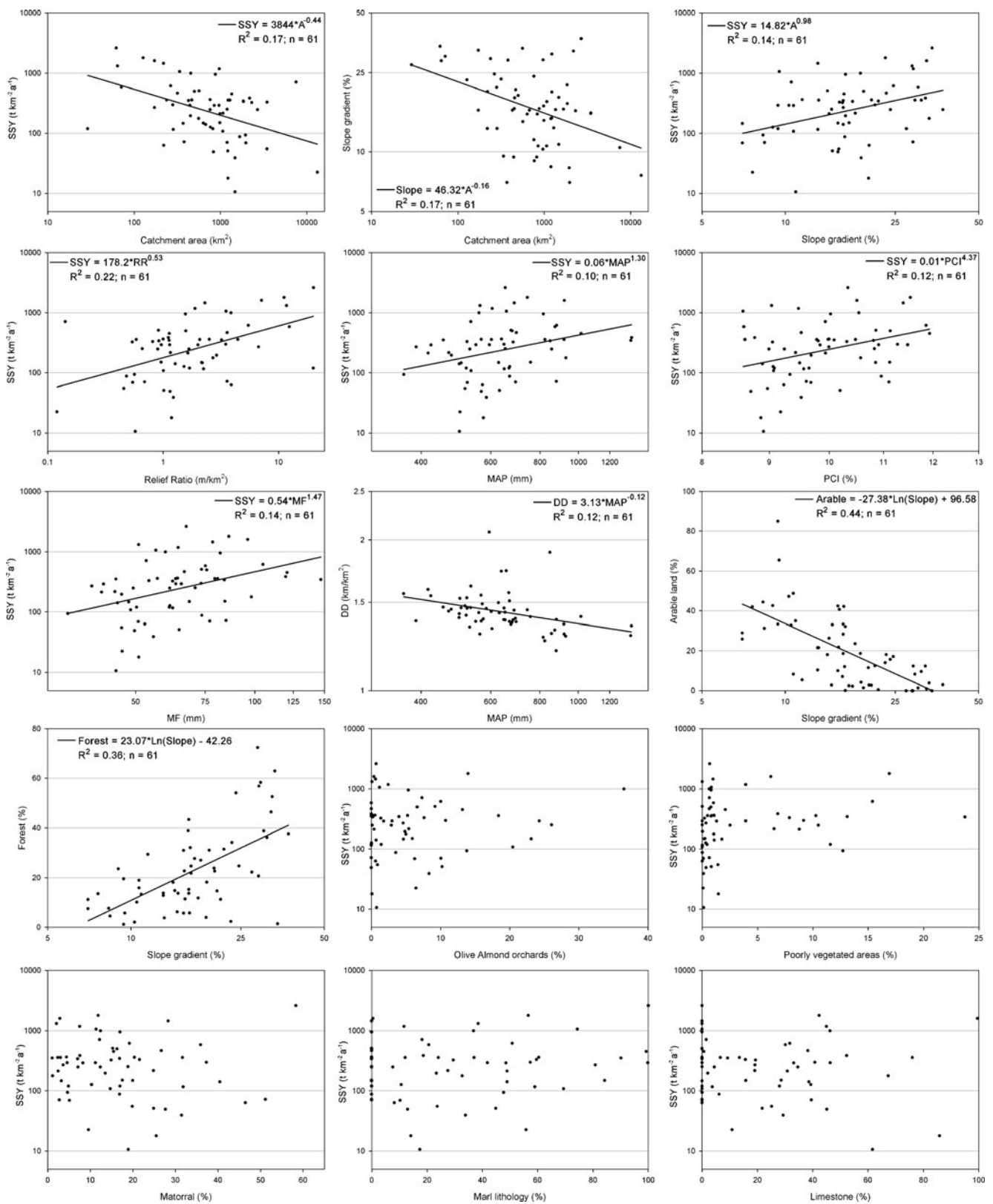


Fig. 2 Scatter plots to illustrate some of the relations found between environmental variables and sediment yield

correlation with SSY and with slope gradient. In other words, large catchments have lower mean slope gradients and lower SSY than small catchments. All climate variables show a positive correlation with SSY, stressing the importance of rainfall amount and seasonality. Perhaps, counterintuitively, a negative correlation was observed between mean annual precipitation and drainage density. Less surprising is that most arable land appears to be on less steep slopes, while on steep slopes, high percentages of forest are found. Although the correlation matrix shows relatively high correlations, the scatter plots of Fig. 2 reveal ambiguous relations between SSY and most land cover and lithology classes, in part due to the many zero observations for these classes. The clearest positive correlations were found between the percentage of poorly vegetated areas (PV) and both SSY and SY, and the percentage olive and almond orchards (OIAlm) and SSY (see Fig. 2 and Table 3).

3.2 Multiple linear regression equations

Because of the lognormal distribution of SY and SSY, the natural logarithm of area-specific sediment yield (lnSSY) and absolute sediment yield (lnSY) were used as dependent variables in multiple linear regression analysis using stepwise forward and backward selection. The models with the highest explanatory value for lnSSY and lnSY respectively are:

$$\begin{aligned} \ln \text{SSY} = & 1.353 + 0.065 * S + 0.108 * RR \\ & + 0.337 * PCI - 0.026 * Mat - 0.013 * Lime \\ & - 0.041 * Meta + 0.038 * Fluv \end{aligned} \quad (8)$$

($R^2=0.55$; $Adj-R^2=0.49$; $ME=0.55$, $RRMSE=0.14$; p value <0.0001 ; $n=61$)

$$\begin{aligned} \ln \text{SY} = & 10.18 + 0.049 * S + 0.011 * MF \\ & + 0.025 * OIAlm - 0.027 * Mat - 0.013 * Lime \\ & - 0.038 * Meta + 0.041 * Fluv + 0.003 * Peri \end{aligned} \quad (9)$$

($R^2=0.57$; $Adj-R^2=0.50$; $ME=0.57$, $RRMSE=0.07$; p value <0.0001 ; $n=61$)

Although there is a relatively high correlation between slope gradient (S) and the Relief Ratio (RR; see Table 3), there is no problem of collinearity in Eq. 8 since the tolerance and variance inflation factor are within acceptable ranges (SAS 1999). The relatively good calibration results are, however, strongly influenced by a few observations as is indicated by the studentised residual of the predictions (i.e. studentised residual >2 or <-2). Based on this criterion, the El Gergal catchment was identified as an outlier for SSY, and the catchments of Embarcaderos,

Riudecañas and Oliana were considered as outliers for SY (Fig. 3). For the Oliana and El Gergal catchments, no explanation was found for the high residual of the predictions, whereas Embarcaderos and Riudecañas represent by far the largest and smallest catchments of the database, respectively, which may be an explanation as to why they appear as outliers. The models were calibrated again without the outliers using a stepwise regression with the same variables, resulting in the following equations for lnSSY and lnSY respectively:

$$\begin{aligned} \ln \text{SSY} = & 1.891 + 0.067 * S + 0.110 * RR \\ & + 0.278 * PCI - 0.029 * Mat - 0.012 * Lime \\ & - 0.042 * Meta + 0.039 * Fluv \end{aligned} \quad (10)$$

($R^2=0.58$; $Adj-R^2=0.52$; $ME=0.58$; $RRMSE=0.13$; p value <0.0001 ; $n=60$)

$$\begin{aligned} \ln \text{SY} = & 6.768 + 0.055 * S + 0.382 * PCI \\ & - 0.025 * Mat - 0.012 * Lime \\ & + 0.059 * Fluv + 0.005 * Peri \end{aligned} \quad (11)$$

($R^2=0.58$; $Adj-R^2=0.53$; $ME=0.58$; $RRMSE=0.06$; p value <0.0001 ; $n=58$)

Again, the tolerance and variance inflation factor indicate that there is no collinearity problem in these equations, so all parameters were maintained.

The main part of variance in SSY is explained by the Relief Ratio (RR), both in the equation with and without outliers (Table 4). All other parameters explain much less of the variance in SSY, with lowest contribution from the percentage of Fluvisols (Fluv), which is also the least significant model parameter, with and without outliers. For SY, the main part of variance is explained by the catchment perimeter (Peri), followed by the Modified Fournier Index (MF). Least variance in SY is explained by the percentage of olive and almond orchards (OIAlm), which together with the percentage of Fluvisols (Fluv) are the least significant model parameters. Without outliers, Peri is the single most significant parameter explaining by far the main part of variance. In the model without outliers, the MF is substituted by the PCI, but with a much lower contribution to the explained variance in SY.

Calibration results of both models were only slightly better without outliers than with all observations (Table 5 and Fig. 3). Therefore, it was decided to validate the models both with and without the outliers using the “Jackknife” procedure as described above (Shao and Tu 1995). When validated for all 61 observations, the R^2 and the ME decrease dramatically compared to the calibration for both SY and SSY (Table 5 and Fig. 4). There is a large scatter around the 1:1 line, and the ME for both models is

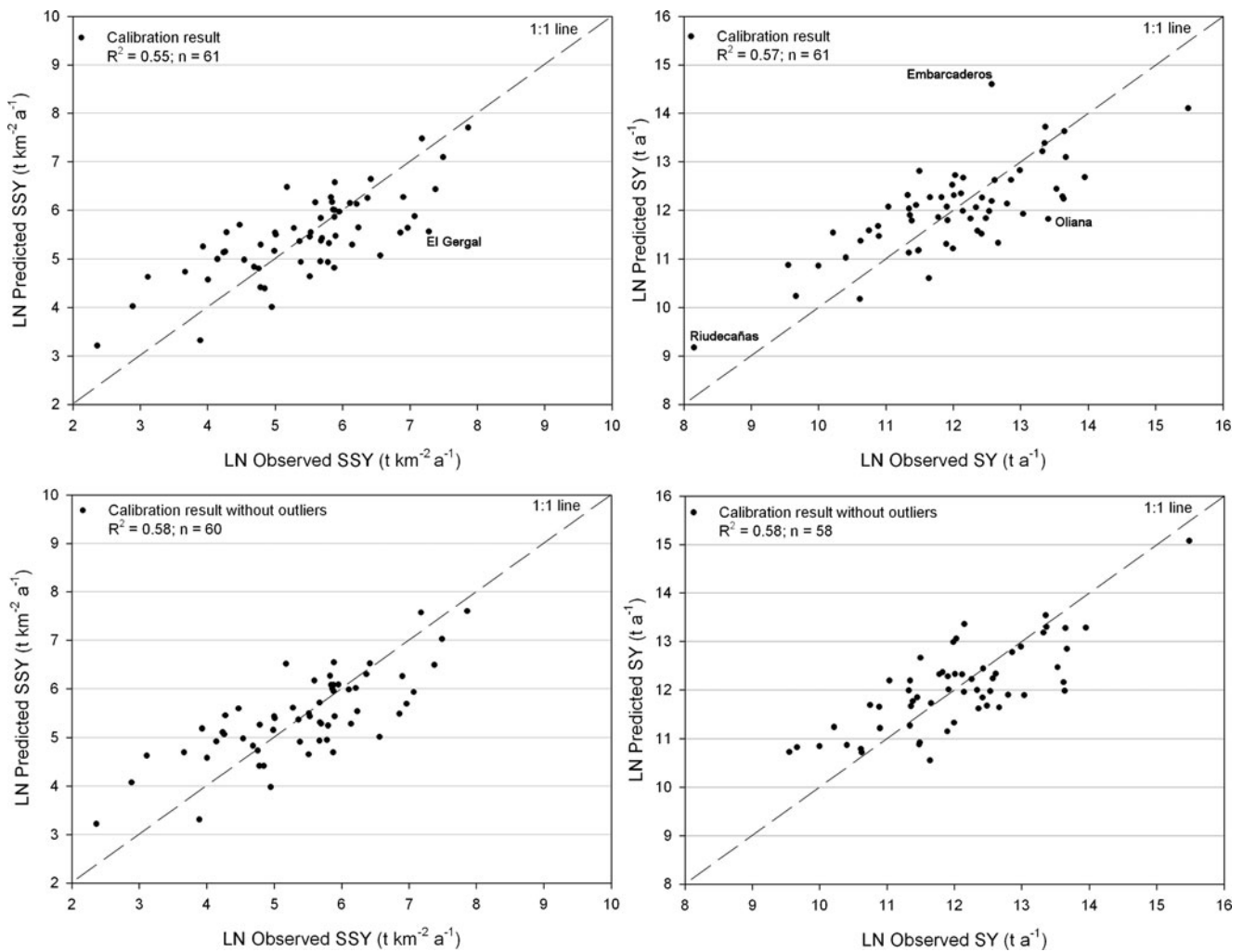


Fig. 3 Calibration results of the multiple linear regression models. Presented are the natural logarithm of predicted and observed area-specific sediment yield (SSY) and absolute sediment yield (SY) with all observations (*upper*) and after removal of outliers (*lower*)

negative, meaning that the model produces more variation than is present in the measured values. Without the outliers, the validation results are better but still far worse than the calibration results. Validation results for SY are slightly better than for SSY, both with and without outliers. For comparison, it was also tested if a log transformation of those variables with a lognormal distribution included in the analysis would provide different results for the regression analysis. Although prediction equations were slightly different, validation results were very similar to those described above. Since normality of explanatory variables is not required for regression analysis, and to maintain the focus of this paper, we do not present all details of this exercise here.

3.3 The ART sediment delivery model

The ART model (Syvitski et al. 2003, 2005) was applied directly for prediction of sediment yield in the 61 Spanish

catchments. Table 6 and Fig. 5 show an evaluation of the quality of the predictions by comparison of predicted and observed sediment yield. Based on the studentised residual of the predictions with the ART model, several outliers were identified, and so, the model was also applied without these outliers (see Table 6 and Fig. 5). For SY, the catchments of Embarcaderos, Cijara and Doña Aldonza appeared as outliers, while for SSY, the outliers were Riudecañas, La Cierva, Conde de Guadalhorce, and El Gergal.

Both with and without outliers, the R^2 of the ART model predictions is relatively high. However, for all ART model predictions, the ME is very low, and the RRMSE is more than 1, meaning that predictions strongly deviate from the line of unity. The model generally overestimates sediment yield (SSY and SY), especially for the lower sediment yield values. Validation results for SSY are better than for SY, both with and without outliers. For SSY, removal of outliers results in a higher R^2 and ME, whereas for SY, removal of outliers results in a higher R^2 but much lower ME.

Table 4 Summary of statistics per variable for the regression equations for area-specific sediment yield (SSY) and absolute sediment yield (SY)

| Variable | Partial R^2 | Standard error | p value | Variable | Partial R^2 | Standard error | p value |
|---------------------------|---------------|----------------|-----------|------------------------|---------------|----------------|-----------|
| SSY Full model ($n=61$) | | | | No outliers ($n=60$) | | | |
| Intercept | | 1.291 | 0.299 | Intercept | | 1.264 | 0.141 |
| S | 0.051 | 0.017 | <0.001 | S | 0.032 | 0.017 | <0.001 |
| RR | 0.154 | 0.032 | 0.001 | RR | 0.165 | 0.031 | <0.001 |
| PCI | 0.031 | 0.123 | 0.008 | PCI | 0.037 | 0.121 | 0.026 |
| Mat | 0.061 | 0.009 | 0.005 | Mat | 0.077 | 0.009 | 0.002 |
| Lime | 0.038 | 0.005 | 0.010 | Lime | 0.065 | 0.005 | 0.011 |
| Meta | 0.080 | 0.010 | <0.001 | Meta | 0.081 | 0.010 | <0.001 |
| Fluv | 0.025 | 0.022 | 0.091 | Fluv | 0.028 | 0.021 | 0.071 |
| SY Full model ($n=61$) | | | | No outliers ($n=58$) | | | |
| Intercept | | 0.505 | <0.001 | Intercept | | 1.283 | <0.001 |
| S | 0.04 | 0.020 | 0.016 | S | 0.023 | 0.016 | 0.001 |
| MF | 0.13 | 0.006 | 0.066 | PCI | 0.022 | 0.116 | 0.002 |
| OIAIm | 0.02 | 0.016 | 0.119 | Mat | 0.045 | 0.008 | 0.005 |
| Mat | 0.05 | 0.009 | 0.005 | Lime | 0.024 | 0.005 | 0.014 |
| Lime | 0.03 | 0.005 | 0.016 | Fluv | 0.061 | 0.021 | 0.007 |
| Meta | 0.06 | 0.011 | <0.001 | Peri | 0.258 | 0.001 | <0.001 |
| Fluv | 0.04 | 0.024 | 0.091 | | | | |
| Peri | 0.21 | 0.001 | <0.001 | | | | |

Indicated are the results with all observations ($n=61$) and after removal of outliers ($n=60$ or 58)

4 Discussion

Based on the calibration of the linear regression equations, it seems that predictions of absolute (SY) and area-specific sediment yield (SSY) are reasonably accurate. There is strong agreement in the environmental factors that appear in the equation for prediction of SY and SSY, and model performances are also comparable. Both regression equations represent at least one variable related to topography, climate, vegetation, lithology and soil characteristics, as such representing a range of environmental factors. Most significant model parameters were related to topographic relief (RR for SSY), catchment size and annual rainfall

distribution (Peri and MF for SY). On the other hand, the poor validation results imply that the models are very unstable and are not useful for extrapolation to other catchments, although after removal of the outliers the validation results became somewhat better. This stresses the importance of performing a model validation and not trusting only calibration results, as is often done in regression studies. This was also confirmed by Verstraeten and Poesen (2001) who found that good regressions in calibration do not always imply good model validation results. Likewise, Grauso et al. (2008) reported that application of regression equations developed for a range of Italian catchments did not yield accurate results for

Table 5 Summary of calibration and validation results of the regression equations for area-specific sediment yield (SSY; $t\ km^{-2}\ a^{-1}$) and absolute sediment yield (SY; $t\ a^{-1}$)

| | Calibration | | | | Jackknife validation | | | |
|----------------|-------------|------|------|------|----------------------|-------|-------|------|
| | SSY | SY | SSY | SY | SSY | SY | SSY | SY |
| Equation nr. | 8 | 9 | 10 | 11 | – | – | – | – |
| R^2 pred-obs | 0.55 | 0.57 | 0.58 | 0.58 | 0.03 | 0.07 | 0.17 | 0.25 |
| ME | 0.55 | 0.57 | 0.58 | 0.58 | –0.63 | –0.22 | –0.10 | 0.17 |
| RRMSE | 0.14 | 0.07 | 0.13 | 0.06 | 0.27 | 0.11 | 0.22 | 0.09 |
| n | 61 | 61 | 60 | 58 | 61 | 61 | 60 | 58 |

R^2 pred-obs R^2 between predicted and observed values, ME model efficiency, RRMSE relative root mean square error, n number of observations included in the analysis

Indicated are the results with all observations ($n=61$) and after removal of outliers ($n=60$ or 58)

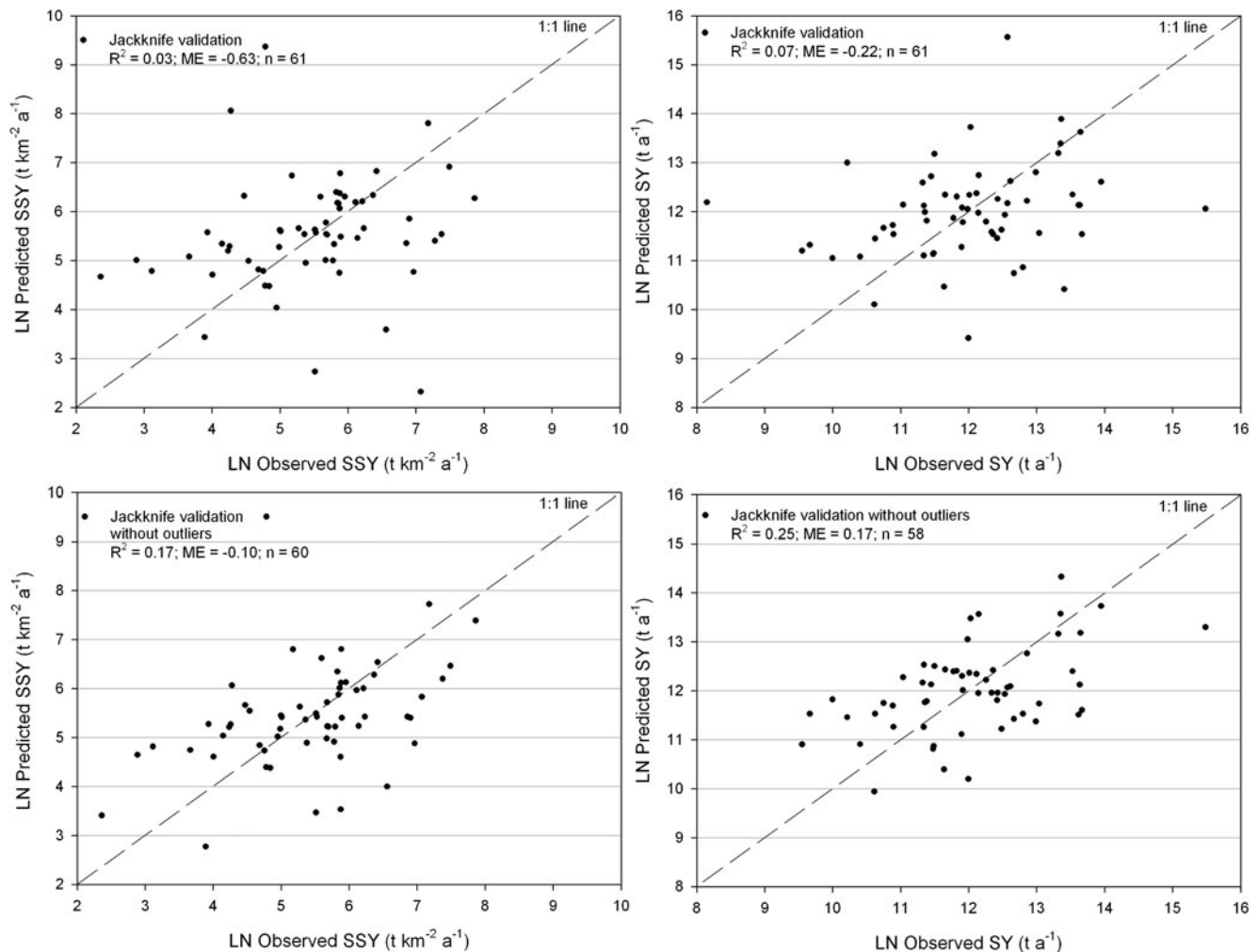


Fig. 4 Jackknife validation results of the multiple linear regression models. Presented are the natural logarithm of predicted and observed area-specific sediment yield (SSY) and absolute sediment yield (SY) with all observations (*upper*) and after removal of outliers (*lower*)

prediction of sediment yield in 16 Sicilian catchments. Yet, still most studies presenting a regression equation include a correlation coefficient for calibration but do not apply a proper validation procedure with independent data (e.g., Delmas et al. 2009; Grauso et al. 2008; Restrepo et al. 2006; Syvitski et al. 2003; Tamene et al. 2006; Verstraeten et al. 2003).

Notwithstanding the use of more variables representing a wider range of environmental characteristics for 61 catchments, the regression in this study was not more stable and did not perform better than the regression equation calibrated for a subset of 22 catchments by Verstraeten et al. (2003). Although fewer variables were used in their analysis, some very similar variables were selected in the stepwise regression of both studies (i.e. Relief Ratio, olive and almond orchards, % Matorral Forest, poorly vegetated areas). Yet, both the regression equations for the 22 and for the present 61 catchments performed worse than the semiquantitative Factorial Scoring Model (FSM) that was

applied to the same catchments and showed better calibration and validation results (i.e. $R^2=0.72$; $ME=0.72$; $RRMSE=0.65$; de Vente et al. 2005). FSM is an expert model where five factors (i.e. topography, lithology, vegetation cover, gullies, catchment shape) are used to characterise a watershed in the vicinity (~5 km) of the reservoir and the main tributaries by providing a score between 1 and 3. An index is calculated by multiplying the five scores, and together with catchment area, this index is used to obtain a regression equation for the prediction of SSY (de Vente et al. 2005, 2006; Verstraeten et al. 2003).

The ART model with only three variables that was calibrated for global rivers (Syvitski et al. 2003) provides much higher R^2 values between predicted and observed sediment yield (SSY and SY) of the Spanish catchments than the linear regression equations (Eqs. 8–11). However, the low ME and high RRMSE of the predictions with the ART model suggest that these are not necessarily better. For most catchments, the ART model strongly overpredicts

Table 6 Validation of the ART model (Syvitski et al. 2003) for area-specific sediment yield (SSY; $t\ km^{-2}\ a^{-1}$) and absolute sediment yield (SY; $t\ a^{-1}$) as observed in the Spanish catchments

| | Validation ART model | | | |
|----------------|----------------------|-------|------|-------|
| | SSY | SY | SSY | SY |
| R^2 pred-obs | 0.38 | 0.17 | 0.54 | 0.31 |
| ME | -0.22 | -0.32 | 0.04 | -2.62 |
| RRMSE | 1.29 | 2.30 | 1.18 | 1.84 |
| n | 61 | 61 | 57 | 58 |

R^2 pred-obs R^2 between predicted and observed values, ME model efficiency, RRMSE relative root mean square error, n number of observations included in the analysis

Indicated are the results with all observations ($n=61$) and after removal of outliers ($n=57$ or 58)

sediment yield. According to Syvitski et al. (2003, 2005), the overestimation of sediment yield can be explained by the fact that reservoirs trap substantial volumes of sediments and therefore reduce the expected sediment yield for

undisturbed conditions. For the Spanish reservoirs, this might indeed explain part of the overestimated sediment yield by the ART model, because there are reservoirs upstream of most of the reservoirs used for the present study. On the other hand, important errors can also be due to factors that are not considered by the model such as human impact (including conservation measures), lithology (de Vente et al. 2005; Woodward 1995) tectonics and the rate of rock uplift (Hovius 1998). Part of these issues may be solved by the BQART model, a successor of the ART model that integrates factors on river discharge (Q), lithology and human impacts, including dams and erosion control measures (B; Syvitski and Milliman 2007). Yet, reliable and detailed information on these factors is often difficult to obtain. It should also be remembered that the ART model was calibrated mostly for large global river basins worldwide. Calibration of the ART model for the Spanish data, similar to that done for the other regression equations, may give much better results.

Although some additional variables may be required, as well as a more regionalised calibration of model parame-

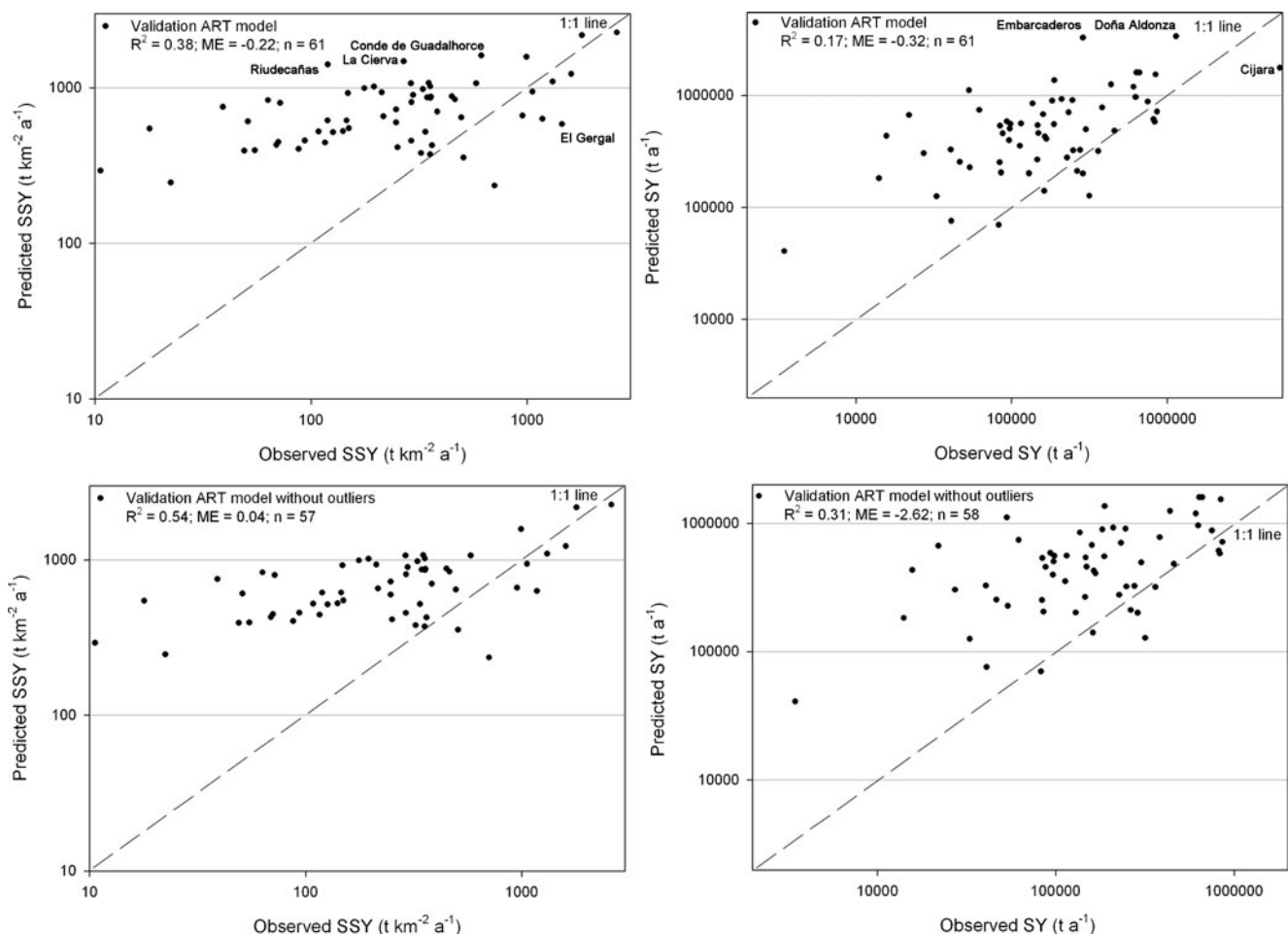


Fig. 5 Validation results of the ART model (Syvitski et al. 2003). Presented are the predicted and observed area-specific sediment yield (SSY) and absolute sediment yield (SY) with all observations (*upper*) and after removal of outliers (*lower*)

ters, it is certainly promising to observe that the ART model with only three variables has the potential for reasonable predictions of sediment yield at the global scale. Moreover, the relevance of these three variables is confirmed by the most significant model parameters in the multiple regression equations of this study. As in the ART model, factors related to topography, catchment size, and climate (RR, Peri, MFI) explained the main part of variation in sediment yield. The RR is a combination of the A and R factor of ART, whereas catchment perimeter is highly correlated with A (see Table 3). On the other hand, the ART model uses temperature instead of a rainfall-related factor. Syvitski et al. (2003) considered temperature as a more complete climate factor than rainfall alone, since temperature relates to the occurrence of convective, high-intensity rainstorms, but also to soil formation, soil erosion, runoff from melting snow, and freeze–thaw cycles (Harrison 2000; Syvitski et al. 2003). The role of mean annual temperature (T_m) was, however, not confirmed by our regression analysis, maybe because the differences in temperature between the Spanish study catchments were not large enough.

There are various possible explanations for the unstable model performance of the linear regression equations. First of all, land use information does not necessarily represent the percentage soil cover by vegetation, whereas the latter is especially important for erosion predictions (Casermeiro et al. 2004; Gyssels et al. 2005; Molina et al. 2007). Secondly, due to land use changes, land use as indicated on the CORINE Land Cover map (CLC2000) may not be representative for land cover conditions during the period for which the measured reservoir sedimentation rates are valid. Large-scale reforestations and extensions of olive and almond orchards that have taken place in the last decades (Cammeraat and Imeson 1999; García-Ruiz 2010; Poesen et al. 1997; Rojo Serrano 2003; van Wesemael et al. 2003) may provide a false view of the soil protection by vegetation during the lifetime of the reservoir. Furthermore, due to the low resolution of the soil and lithology maps, important detail is probably missed, and so, a higher resolution may increase the explanatory value of these variables. Next, drainage density is a typical example of a scale-dependent variable (Abrahams 1984; Vogt et al. 2003). In this study, we automatically extracted a river network from a DEM, using a threshold of 0.2 km^2 , and used this river network to calculate the drainage density. Surprisingly, a (nonsignificant, p value of 0.08) negative correlation was found between drainage density and SSY, and no correlation was observed with SY, which contrasts with various studies that considered drainage density to be strongly related to both sediment yield and mean annual precipitation (Abrahams 1984; Langbein and Schumm 1958). In agreement with our results, some studies reported a decreasing or complex correlation between drainage

density and mean annual precipitation (Abrahams 1984), whereas others reported an increasing drainage density with increasing precipitation (Daniel 1981). Most studies explained the relation between mean annual precipitation and drainage density by differences in vegetation cover and runoff generation under diverse climatic conditions. In our analysis, however, drainage density did not appear as a significant variable in any of the multiple regression models (alpha 5%). A better result may be obtained when additional information on lithology, vegetation cover and climate is used to determine the threshold value in a stratified manner (Colombo et al. 2007; Vogt et al. 2003), or when drainage density is extracted from aerial photographs (Allen 1986).

Errors in the measured sediment yield and in the source data of the explanatory variables may also explain part of the poor model validation results. Furthermore, the variation in environmental conditions and in the dominant erosion and sediment transport processes between the 61 catchments may be too large to be explained by one single regression equation, or it may be that important explanatory variables were missing in the analysis. For example, mean annual runoff-related variables might explain an important part of mean annual sediment yield (Restrepo et al. 2006; Syvitski et al. 2003). Comparison of soil loss rates obtained from field plot studies with reservoir sedimentation rates in Mediterranean environments also suggests that gully erosion, mass movements and bank erosion are mainly responsible for sediment export at the catchment scale (de Vente et al. 2007, 2008; Poesen and Hooke 1997; VanMaercke et al. 2011). These processes operate at distinct locations in the landscape, and factors controlling these processes are difficult to parameterise by one single value for the entire catchment.

Many of the possible improvements to deal with the abovementioned problems require a major amount of additional processing and input of data that are often not easily available for large watersheds. Yet, at least equally important as data quality is the model concept used. Apart from different variables used for prediction, some models multiply factors (ART and FSM), while other models use the sum of variables (regression). Based on the current information, it seems that those models accounting for the interaction between environmental factors and for nonlinear relations through multiplying factors and by using power functions, such as the FSM and ART models, potentially perform better than linear models such as the linear regression models (de Vente 2009).

Although the linear regression model was not stable, the correlation analysis and regression equations do provide more insight into relevant relations between environmental factors and sediment yield, and increase our understanding of sediment dynamics at the catchment scale. This helps to

identify important factors that constrain erosion and sediment transporting processes, and to select factors to be considered in more sophisticated model approaches. For example, the negative relation between catchment area and SSY that was found in this study is often reported in the literature, and is explained by the fact that during transport of sediments through a catchment, increasingly more sediment is trapped on footslopes, alluvial plains and other sinks, while erosion rates decrease due to decreasing hillslope gradients downstream (de Vente et al. 2007; Walling 1983). This theory is supported by the negative correlation between catchment area and mean hillslope gradient and the positive correlation between slope gradient and SSY observed in this study. Furthermore, our results suggest a positive correlation between mean annual precipitation and sediment yield, although the increase in sediment yield with annual rainfall is not as strong as was reported for Moroccan catchments (Woodward 1995). This uninterrupted, positive relation deviates from the relations suggested in earlier studies where SSY often first increases and then decreases with increasing mean annual rainfall (Langbein and Schumm 1958; Walling and Kleo 1979; Wilson 1973). This trend is still frequently referred to and was originally explained by low runoff rates and the absence of a protective vegetation cover in areas with very low precipitation amounts, and the presence of a vegetation cover protecting the soil beyond a certain threshold of annual precipitation (Langbein and Schumm 1958). The deviation from these trends in Spain and Morocco may be due to widespread human disturbances that impede a direct relation between rainfall amounts and vegetation cover that is expected in areas with a more natural vegetation cover.

For practical applications and to support policy decisions in a given region, regression equations form an attractive option because they are relatively easily applicable and it is tempting to apply an existing equation. However, the results of this study confirm that the use of regression equations beyond the region and conditions for which the model was developed is not a guarantee of good results. Furthermore, the regression analysis is based on lumped variables, which allows prediction of sediment yield but does not identify where the sediments originate, where erosion problems are most severe, or which erosion and sediment transport processes are dominant. To answer these questions, other spatially distributed approaches are required.

5 Conclusions

Correlation analysis reveals that, for 61 Spanish catchments, drainage area, catchment perimeter, stream length, relief ratio, the Modified Fournier Index and the percentage

poorly vegetated areas have the highest correlation coefficients with area-specific (SSY) and absolute (SY) sediment yield. However, a combination of topographic, climatic, lithologic, vegetation and soil variables is required to provide the best linear regression equation to predict sediment yield. Although calibration results after a stepwise regression are reasonably good, validation of these equations shows that they are very unstable and cannot be used for extrapolation. On the other hand, application of the ART sediment delivery model (Syvitski et al. 2003) for prediction of sediment yield in the Spanish catchments shows a relatively high correlation between predicted and observed values, although predictions systematically overestimate observed sediment yield. Beside measurement errors in sediment yield and in the explanatory variables, there are various explanations for the poor model validation results in general: (1) not all controlling erosion and sediment transport processes are well represented by the available data; (2) land use is not representative of vegetation cover; (3) the land use, lithology and soil data are of a too low resolution; (4) land use is not a static property and will have changed during the lifetime of the reservoirs; and (5) nonlinear relations between sediment yield and environmental variables, and nonlinear interactions between those variables are not (sufficiently) accounted for by the models.

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