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Progress in Physical Geography 2007; 31; 155

DOI: 10.1177/0309133307076485

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The sediment delivery problem revisited

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Abstract: Understanding the sediment delivery process at the drainage basin scale remains a challenge in erosion and sedimentation research. In the absence of reliable spatially distributed process-based models for the prediction of sediment transport at the drainage basin scale, area-specific sediment yield (SSY; $\text{t km}^{-2} \text{ y}^{-1}$) is often assumed to decrease with increasing drainage basin area (A). As the measurement of A is relatively simple, this assumption is frequently used for prediction of SSY in ungauged basins. However, over the last two decades several studies reported a positive or non-linear relation between A and SSY. Various authors have suggested diverse explanations for these opposing trends. This paper provides an overview of the different observed trends and summarizes the explanations for each trend. Furthermore, three typical trends are identified to conceptualize the main driving forces of the relation between A and SSY. First of all, it is emphasized that erosion and sediment deposition processes are scale dependent, and going from small (m^2) to larger areas (km^2) more erosion processes become active leading to a rise in SSY with increasing A. However, for larger areas ($>\text{km}^2$) erosion rates generally decrease and deposition in sediment sinks increases due to decreasing slope gradients, and so SSY decreases with increasing A. Next, land-cover conditions and human impact determine if hillslope erosion is dominant over channel erosion or *vice versa*. In the first case, SSY is expected to decrease with increasing A, while in the latter case SSY will show a continuous positive relation with A. Only for very large areas ($A > \sim 10^4 \text{ km}^2$) a decrease in SSY is observed when drainage density decreases or channel banks are stabilized. Finally, spatial patterns in lithology, land cover, climate or topography can cause SSY to increase or decrease at any basin area and can therefore result in non-linear relations with A. Altogether, with increasing A often first a rise and then a decrease in SSY is observed. The decrease can be absent or can be postponed within a region due to local factors of which lithology, land cover, climate and topography are the most important ones. The large regional, local and even temporal variability in the trend between A and SSY implies that prediction of SSY based on A alone is troublesome and preferably spatially distributed information on land use, climate, lithology, topography and dominant erosion processes is required.

Key words: erosion processes, modelling, scale, Sediment Delivery Ratio, sediment transport, sediment yield.

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I Introduction

In his well-known publication on 'the sediment delivery problem', Walling (1983) pleaded for continuous research towards an increased understanding of the sediment delivery process in order to link onsite erosion to sediment yield at the basin outlet. Since then, there has been important progress in spatially distributed modelling of soil erosion and sediment transport. However, the high data requirements and the inability to include all relevant erosion and sediment transport processes still hamper accurate prediction of sediment yield at the drainage basin scale using these models (Merritt *et al.*, 2003; de Vente and Poesen, 2005). On the other hand, many studies reported a decreasing area-specific sediment yield (SSY; $\text{t km}^{-2} \text{y}^{-1}$) with increasing drainage basin area (A ; km^2) (eg, Dendy and Bolton, 1976; Milliman and Meade, 1983; Milliman and Syvitski, 1992; Summerfield and Hulton, 1994; Einsele and Hinderer, 1997; Radoane and Radoane, 2005; Renwick *et al.*, 2005). This negative relation between A and SSY has often been extrapolated to make predictions of sediment yield for ungauged basins at regional or even at global scale (eg, Milliman and Meade, 1983; Milliman and Syvitski, 1992; Syvitski *et al.*, 2003; 2005; Renwick *et al.*, 2005) using the equation:

$$\text{SSY} = \alpha A^\beta \quad (1)$$

where A stands for drainage basin area (km^2), and α and β are empirical parameters. In addition, it is generally assumed that the slope (β) of the equation linking A and SSY is analogue to the slope of the relation between A and the sediment delivery ratio (SDR) (Walling and Kleo, 1979; Walling, 1983; Lu *et al.*, 2006). The SDR refers to the ratio between SSY ($\text{t km}^{-2} \text{y}^{-1}$) and gross erosion ($\text{t km}^{-2} \text{y}^{-1}$) as (Maner, 1958; Walling, 1983):

$$\text{SDR} = \frac{\text{SSY}}{\text{gross_erosion}} \quad (2)$$

The SDR is frequently used in erosion studies to calculate SSY at the basin outlet from

estimated gross erosion rates (eg, Gottschalk, 1957; Maner, 1958; Boyce, 1975; Vanoni, 1977; Brath *et al.*, 2002; Lim *et al.*, 2005; Syvitski *et al.*, 2005).

The decreasing SSY with increasing A is often explained by the fact that, during transport through a river basin, progressively more sediment is trapped in footslopes, concavities, alluvial plains and other sinks, while erosion rates do not increase or even decrease due to decreasing hillslope gradients downstream. Nevertheless, in his publication on the sediment delivery problem, Walling (1983) already clearly pointed at the limitations of the sediment delivery ratio (SDR) for prediction of SSY. Although often a negative relation is apparent, Walling (1983) emphasized the uncertainties with respect to temporal and spatial lumping of data on sediment transport, sediment yield and explanatory factors such as climate, land use and lithology. Lu *et al.* (2005) and Parsons *et al.* (2006b) also questioned the validity of a spatial and temporal uniform sediment delivery concept and stressed the fact that the SDR depends on the timescale over which erosion rates and sediment yields are measured. Walling and Webb (1996) commented that the generally accepted negative relationship between A and SSY is mainly based on studies in regions heavily impacted by human activity such as the USA. Global reality, however, is much more diverse than this and therefore more detailed analysis of sediment yield data from different regions of the world is required (Walling and Webb, 1996).

Over the last two decades there has been an increased interest in the relation between A and SSY. Various studies have revealed cases where a very poor relation, a positive relation or a combination of a positive and negative relation between A and SSY was found (eg, Church and Slaymaker, 1989; Gögüs and Yener, 1997; Lane *et al.*, 1997; Krishnaswamy *et al.*, 2001; Schiefer *et al.*, 2001; Dedkov, 2004; García Ruiz *et al.*, 2004; de Araújo and Knight, 2005; de Vente and Poesen, 2005; Haregeweyn *et al.*, 2005;

Jiongxin and Yunxia, 2005; de Vente *et al.*, 2006; Restrepo *et al.*, 2006). The explanations for the absence of a negative relation are diverse, as are the spatial scales at which the studies were performed. However, the results of these studies undoubtedly have important implications for the prediction of sediment yield using the relation with basin area and for our understanding of sediment yield dynamics at the basin scale in general. Therefore, the objective of this paper is to provide an overview of the different relations between A and SSY as reported in literature, and to explore explanations for the differences in the observed trends. It is anticipated that this will help to increase our understanding of sediment delivery and sediment yield estimates at the basin scale.

II Negative relations between basin area and sediment yield

There have been various attempts to relate area-specific sediment yield (SSY) to drainage

basin area (A). Figure 1 illustrates the relation between A and SSY based on published sediment yield data of 877 rivers worldwide. The source of these data is diverse and is discussed in more detail in the following paragraphs (see also Figure 2 and 3). Based on these data there appears to be a slightly negative relation between A and SSY as:

$$SSY = 370.46 * A^{-0.08} \quad (R^2 = 0.02, n = 877, p < 0.0001) \quad (3)$$

The relation is statistically significant although the explained variance is very low. However, the relation becomes more pronounced after stratification of the data according to geographical region or maximum basin altitude. This is illustrated in Figure 2 which provides various examples of a decreasing SSY with increasing A and represents a selection of the data presented in Figure 1. All the relations in Figure 2, except for Iran, Algeria and Israel, are significant at

Figure 1 Scatter plot of worldwide sediment yield (SSY) data against drainage basin area (A). For references of the data sources, see Figures 2 and 3

Figure 2 Examples of a negative relation between basin area (A) and sediment yield (SSY) for various basins worldwide. For each relation, the regression statistics and significance level (p-value) are indicated

Sources of the data: 1, 2, 3, 4, 8, 11, 14 – Milliman and Syvitski, 1992; 7 – Tidjani *et al.*, 1998; 9 – Avendaño Salas *et al.*, 1997; 10 – Radoane and Radoane, 2005; 12 – Albergel *et al.*, 2000; 6 – Lahlou, 1996; 5 – Lahlou, 1996; Fox *et al.*, 1997; 13 – Inbar, 1992; 15 – Dendy and Bolton, 1976; 16, 17 – Arabkhedri *et al.*, 2004; 18 – Verstraeten and Poesen, 2001. Data from 15 (USA) were not included in the overall regression equation because the individual data points were not available.

5% confidence level and the explained variance (R^2) ranges between 0.03 and 0.84.

Beside the relation with A the data reported by Milliman and Syvitski (1992) show the effect of topography on SSY (see Figure 2, relations 1, 2, 3, 4, 8, 11 and 14). In fact, they use maximum altitude as a surrogate for topographic relief difference. Small basins have a higher SSY than larger basins, but, for basins with the same A , mountainous areas have a higher SSY than areas of moderate relief and lowlands. This trend was also observed by Einsele and Hinderer (1997) in the analysis of worldwide sediment yield data. Therefore, Milliman and Syvitski (1992) mention basin area and maximum altitude as the major controls of sediment yield, whereas climate, land use and geology are of secondary importance. Encouraged by these results, Syvitski *et al.* (2005) estimated absolute sediment yield ($t\ y^{-1}$) in rivers all over the world based on an assumed global relation between basin area and sediment yield in combination with a relief ratio and an estimated mean surface temperature. Although Syvitski *et al.* (2005) calculated absolute sediment yield, the relation they used between basin area and sediment yield suggests that the value of β in equation 1 for worldwide estimates is -0.5 .

The scaling factor β in equation 1 contains important information about basin's sediment transport processes. Although the trend between basin area and SSY as illustrated in Figure 1 seems rather uniform, a more detailed analysis reveals that the slope of the relation (β) shows significant regional variation. Reported values of β vary between -0.06 and -0.85 , and even positive values of β between 0.01 and 0.28 were reported pointing at an increasing SSY with increasing basin area (see Table 1). Moreover, there are also large differences in the value of α in equation 1 (see Figure 2). This means that there is a huge range in observed sediment yield values, up to four orders of magnitude, for basins with the same drainage basin area. So, although a significant negative relation is

often present, A alone explains only a small part of the variation in SSY. Beside basin area, sediment yield is closely related to other basin characteristics such as topography, climate, lithology, land use and vegetation cover.

III Positive relations between basin area and sediment yield

As indicated by the positive values of β in Table 1, SSY not always decreases with increasing A . On the contrary, various studies reported an increasing SSY with increasing A or in some cases the absence of a clear relation. Figure 3 presents a selection of the data shown in Figure 1 for which a positive relation was reported between A and SSY. Although all data together in Figure 3 show a significant positive relation between A and SSY with an explained variance of 0.13 , most of the individual relations are not significant and show a rather low explained variance (R^2 between 0.0003 and 0.14). The most distinct example of a positive relation between A and SSY was found in various regions of Canada (Church and Slaymaker, 1989; Church *et al.*, 1999; Schiefer *et al.*, 2001; Slaymaker *et al.*, 2003). The positive trend in Canada was explained by the remobilization of large volumes of unconsolidated sediments that were delivered to the major valleys during periods of glaciation. Glaciers, hillslope and channel instability were found to be the major eroding processes (Church and Slaymaker, 1989; Church *et al.*, 1999). Some exceptions on these positive trends between A and SSY in Canada were found in flat lying plateaus and major valleys with limited relief (Schiefer *et al.*, 2001), and in the eastern prairies characterized by intense agriculturally disturbed landscapes (Church *et al.*, 1999). In these areas, the conventional negative relation between A and SSY was observed.

Other examples of increasing SSY with increasing A were reported by Dedkov and Moszherin (1992) and Dedkov (2004), based on the analysis of suspended sediment yield in 1872 mountain rivers worldwide and 352 rivers in the plains and low mountain

Table 1 Examples of reported values of β in equation 1 representing the slope of the relation between basin area and area-specific sediment yield (SSY). Positive and negative β values are listed separately

Location	β	N	Basin area (km ²)	Characteristics	Reference
<i>Negative β values</i>					
Large rivers worldwide	-0.85	65	>~1000	>10*10 ⁶ t/yr sediment yield	(Milliman and Meade, 1983)
Rivers worldwide	-0.54	20	~1000-10*10 ⁶	Max elevation > 3000 m	(Milliman and Syvitski, 1992)
Rivers N/S America, Africa, Alpine Europe	-0.46	41	~200-10*10 ⁶	Max elevation 1000-3000 m	"
Rivers South Asia and Oceania	-0.46	90	~200-1*10 ⁶	Max elevation 1000-3000 m	"
Rivers non-Alpine Europe and High Arctic	-0.39	10	~100-100.000	Max elevation 1000-3000 m	"
Rivers worldwide	-0.59	55	~100-2*10 ⁶	Max elevation 500-1000 m	"
Rivers worldwide	-0.34	43	~100-2*10 ⁶	Max elevation 100-500 m	"
Rivers worldwide	-0.20	15	~200-90.000	Max elevation <100 m	"
USA	-0.16	800	~3-80.000	Country wide reservoir data	(Dendy and Bolton, 1976)
USA, New England	-0.21	9	~0.001-100.000	-	(Renwick <i>et al.</i> , 2005)
USA, Mid Atlantic	-0.11	59	~0.001-100.000	-	"
USA, South Atlantic-Gulf	-0.21	61	~0.001-100.000	-	"
USA, Great Lakes	-0.31	51	~0.001-100.000	-	"
USA, Ohio	-0.11	175	~0.001-100.000	-	"
USA, Tennessee	-0.20	43	~0.001-100.000	-	"
USA, Upper Mississippi	-0.06	128	~0.001-100.000	-	"
USA, Lower Mississippi	-0.31	37	~0.001-100.000	-	"
USA, Souris-Red-Rainy	-0.22	23	~0.001-100.000	-	"
USA, Missouri	-0.27	311	~0.001-100.000	-	"
USA, Arkansas-White-Red	-0.12	236	~0.001-100.000	-	"
USA, Texas-Gulf	-0.13	126	~0.001-100.000	-	"
USA, Rio Grande	-0.25	52	~0.001-100.000	-	"
USA, Upper Colorado	-0.32	38	~0.001-100.000	-	"
USA, Lower Colorado	-0.08	79	~0.001-100.000	-	"
USA, Great Basin	-0.15	22	~0.001-100.000	-	"
USA, Pacific Northwest	-0.21	109	~0.001-100.000	-	"
USA, California	-0.20	210	~0.001-100.000	-	"
Central Belgium	-0.40	26	~0.07-50	-	(Verstraeten and Poesen, 2001)
Romania	-0.17	49	~0.1-50.000	Flysch mountain area	(Radoane and Radoane, 2005)
Romania	-0.22	35	~0.1-25.000	Neogene molasses area	"

(Continued)

Table 1 Continued

Location	β	N	Basin area (km ²)	Characteristics	Reference
Romania	-0.28	11	~1-10000	Neogene molasses and quaternary deposits	(Radoane and Radoane, 2005)
Romania	-0.10	12	~1-100.000	Crystalline mountains	"
Romania	-0.18	18	~1-100.000	Neogene molasses area	"
Romania	-0.19	6	~5-4000	Getic Piedmont	"
Romania	-0.12	4	~1-1000	Crystalline mountains area	"
Romania	-0.01	8	~1-7000	Crystalline mountains	"
Romania	-0.32	15	~1-20.000	Moldavian plateau	"
Romania	-0.43	13	~0.4-30.000	Moldavian plateau and Moldova plain	"
Romania	-0.28	12	~1-5000	Oltenia plain	"
Romania	-0.22	12	~0.5-4000	Crystalline and volcanic mountain area	"
Romania	-0.07	17	~1-100.000	Internal flysch area	"
Spain	-0.44	60	~30-17.000	Mediterranean	(Avendaño Salas <i>et al.</i> , 1997)
Algeria	-0.42	15	~130-22.000	—	(Tidjani <i>et al.</i> , 1998)
Tunisia	-0.64	23	~0.8-18	—	(Albergel <i>et al.</i> , 2000)
Tunisia	-0.37	14	~50-18.000	—	(Lahlou, 1996)
Morocco	-0.43	17	~100-50.000	—	(Lahlou, 1996; Fox <i>et al.</i> , 1997)
Israel	-0.41	17	~15-1500	—	(Inbar, 1992)
Iran, Kashaf-Rood	-0.19	9	~50-15.000	—	(Arabkhedri <i>et al.</i> , 2004)
Iran, Markazi (central plateau)	-0.12	39	~30-17.000	—	"
<i>Positive β values</i>					
Italy	0.28	44	~10-650	Mediterranean	(Bazzoffi, 1987; Tamburino <i>et al.</i> , 1990; Bazzoffi <i>et al.</i> , 1996)
Turkey	0.06	17	~70-26.000	—	(Gögüs and Yener, 1997)
Iran, Persian Gulf	0.20	67	~30-25.000	—	(Arabkhedri <i>et al.</i> , 2004)
Iran, Caspian sea	0.24	64	~36-50.000	—	"
Iran, Daryacheh-e-Orunieh	0.07	30	~50-8000	—	"

(Continued)

Table 1 Continued

Location	β	N	Basin area (km ²)	Characteristics	Reference
Colombia, Magdalena river	0.01	32	~200–60.000	Nested subcatchments	(Restrepo <i>et al.</i> , 2006)
Canada	0.26	165	~0.1–100.000	–	(Church <i>et al.</i> , 1999)
USA, Idaho	0.03	32	~0.2–35.000	long-term and contemporary	(Kirchner <i>et al.</i> , 2001)
Ethiopia, Tigray	0.01	10	~0.7–25	–	(Haregeweyn <i>et al.</i> , 2006)

temperate areas of Eurasia. In these studies, the presence of a positive relation between A and SSY was linked to the presence of a well-developed vegetation cover, limited human disturbance, and a dominance of channel erosion over hillslope erosion processes (ie, sheet, rill and ephemeral gully erosion). In contrast, an inverse relation between A and SSY was found characteristic for intensely cultivated basins with an important contribution of hillslope erosion processes to sediment yield (Dedkov and Moszherin, 1992; Dedkov, 2004). Similarly, Church *et al.* (1999) and Slaymaker *et al.* (2003) suggested that a negative relation between A and SSY can be attributed to deposition of sediments during transport and channel aggradation, whereas a positive relation between A and SSY indicates recruitment of sediment along a channel and channel degradation, possibly in combination with substantial delivery of sediments to the main rivers by massive landsliding. This is also in agreement with Renwick and Andereck (2006) who found a clear negative trend between A and SSY for intensively cultivated catchments in Ohio (USA) and an unclear or slightly positive trend for catchments dominated by forest land use.

The influence of dominant erosion processes on the A–SSY relation was also demonstrated by a modelling approach using the physics-based model SHETRAN (Ewen *et al.*, 2000). Model simulations with SHETRAN illustrated that the A–SSY relation is controlled by the dominance of either

channel or hillslope erosion (Birkinshaw and Bathurst, 2006). A positive relation was found when channel erosion is dominant, whereas a negative relation was found where hillslope erosion is the dominant process. Furthermore, the model simulations illustrated the importance of the spatial pattern of land use and rainfall. Severe erosion in the headwaters due to a poor vegetation cover or intense rainfall caused a pronounced negative trend between A and SSY, while intense erosion downstream forced the relation to be more positive (Birkinshaw and Bathurst, 2006). Similarly, using a simple conceptual model in which hillslope erosion, channel erosion, hillslope transport and channel transport were treated separately, Lu *et al.* (2005) demonstrated that the SDR–A relation depends on the dominance of either hillslope or channel erosion processes. Besides, the model showed that spatial heterogeneity of sediment sources and sinks can cause SSY to be independent of A or even increase with A.

The importance of the spatial patterns of climate and land-use characteristics was also demonstrated in a study of SSY in a humid tropical basin of Costa Rica (Krishnaswamy *et al.*, 2001). In this study an increase in SSY from 112 to 404 t km⁻² y⁻¹ was found with an increasing basin area from 318 to 4767 km². This positive trend was explained by the fact that the lower-lying alluvial fans of the basin are predominantly used for intensive agriculture and are exposed to highly erosive rainfall, while the higher-elevation regions are

- (1) Ethiopia: $SSY = 712.32A^{0.01}$ ($R^2=0.02$, $n=10$, $p=0.75$)
 (2) Italy: $SSY = 103.6A^{0.28}$ ($R^2=0.05$, $n=44$, $p=0.15$)
 (3) Iran, Persian Gulf: $SSY = 57.3A^{0.20}$ ($R^2=0.07$, $n=67$, $p=0.07$)
 (4) Iran, Caspian Sea: $SSY = 44.3A^{0.24}$ ($R^2=0.14$, $n=64$, $p=0.002$)
 (5) Iran, Daryacheh-e-Orumieh: $SSY = 124.4A^{0.07}$ ($R^2=0.01$, $n=30$, $p=0.56$)
 (6) Turkey: $SSY = 39.28A^{0.06}$ ($R^2=0.012$, $n=17$, $p=0.67$)
 (7) USA, Idaho, long-term: $SSY = 120.5A^{0.03}$ ($R^2=0.03$, $n=32$, $p=0.32$)
 (8) USA, Idaho, contemporary: $SSY = 9.35A^{0.03}$ ($R^2=0.02$, $n=30$, $p=0.44$)
 (9) Colombia, Magdalena river: $SSY = 452.86A^{0.01}$ ($R^2=0.0003$, $n=32$, $p=0.93$)
 — — All data (excl. 10, 11): $SSY = 67.01A^{0.18}$ ($R^2=0.13$, $n=326$, $p<0.0001$)
 (10) Canada: $SSY = 8.27A^{0.26}$ ($R^2=0.31$, $n=165$, $p<10^{-6}$)
 (11) Eurasia sparsely-uncultivated basins in the plains/low mountain temperate areas ($n=155$).

Figure 3 Examples of a positive relation between basin area (A) and sediment yield (SSY) for various basins worldwide. For each relation, the regression statistics and significance level (p -value) are indicated

Sources of the data: 1 – Haregeweyn *et al.*, 2006; 2 – Bazzoffi, 1987; Tamburino *et al.*, 1990; Bazzoffi *et al.*, 1997; de Vente *et al.*, 2006; 3, 4, 5 – Arabkhedri *et al.*, 2004; 6 – Göğüs and Yener, 1997; 7, 8 – Kirchner *et al.*, 2001; 9 – Restrepo *et al.*, 2006; 10 – Church *et al.*, 1999; 11 – redrawn from Dedkov, 2004. Data from 10 and 11 were not included in the overall regression equation because the separate data points were not available

well protected by a forest, pastures and tree crops resulting in lower erosion rates.

The absence of a significant relation between A and SSY was observed in an overview of sediment yield data based on sedimentation rates in 372 European reservoirs and ponds, although after stratification of the database to individual countries some significant positive as well as negative relations were observed (Verstraeten *et al.*, 2006). Comparable results for Europe were found in a study of four large European rivers (Schaller *et al.*, 2001). Here, a slightly negative relation between A and SSY was found only for the river Meuse, whereas the other rivers showed no clear relation (Neckar and Regen River) or a slightly positive relation (Loire River). In the same study, estimated long-term (10–40 kyr) erosion rates, based on analysis of cosmogenic nuclides, showed no clear relation with basin area for any of the four basins. On the other hand, spatial differences in lithology and topography within the catchments were reflected in the long-term erosion rates that were measured along the river streams.

In a study of 32 forested granitic catchments in Idaho (USA), measured long-term (~5–27 kyr) as well as contemporary (~10–84 yr) SSY showed a slightly positive (not significant) relation with A (Kirchner *et al.*, 2001) (see Figure 3). The authors explain the absence of a negative relation between A and SSY by the presence of narrow steep, V-shaped valleys, with minimal opportunities for sediment deposition during transport downstream. Moreover, it seems likely that in these well-vegetated basins channel erosion is dominant over hillslope erosion processes causing SSY to increase with A, as was suggested earlier by the studies of Dedkov and Moszherin (1992) and Dedkov (2004). Kirchner *et al.* (2001) explain the discrepancy between long-term and contemporary SSY values by the importance of catastrophic erosion events for long-term SSY. Moreover, on long timescales it is expected that close to 100% of the sediments will be delivered to the basin outlet without

significant deposition losses (Lu *et al.*, 2005) causing the absence of a clear relation between A and SSY.

IV Complex relations between basin area and sediment yield

Various authors have emphasized the scale dependency of sediment yield and have provided examples of a complex non-linear relation between A and SSY (eg, Lane *et al.*, 1997; Osterkamp and Toy, 1997; de Vente and Poesen, 2005; Jiongxin and Yunxia, 2005; Fang *et al.*, 2006; Slaymaker, 2006). Figures 4 and 5 give some examples of a complex relation with both increases and decreases in SSY at various spatial scales. For example, Osterkamp and Toy (1997) illustrated the scale dependency of active erosion and deposition processes and SSY with measured data at various scales from both semi-arid and humid conditions in the USA (see Figure 5, A and B). They stated that at small scales, where splash and sheet erosion are the dominant erosion processes, SSY is relatively low. With increasing A more erosion processes become active (ie, rill erosion, gully erosion, channel erosion, landslides) leading to a rise in SSY with increasing A. This rise in SSY continues until a threshold in A is reached beyond which SSY starts to decrease with increasing A due to decreasing slope gradients, resulting in reduced erosion rates and significant sediment storage on foot-slopes, in dry channels, floodplains and other sinks. Although the trends in both regions are comparable, SSY at all scales is higher in the semi-arid environment of Walnut Gulch (Figure 5A) than in the humid Susquehanna River basin (Figure 5B).

For Spain and Italy, a comparable trend was observed as the one reported by Osterkamp and Toy (1997). Figure 4 shows SSY data obtained from runoff plot measurements, volumetric rill and gully measurements (only for Spain) and reservoir sedimentation surveys in Spain and Italy. Table 2 shows the source data of individual Italian erosion plot studies presented in Figure 4. The data of the Spanish example were discussed in detail by

Figure 4 Relation between drainage basin area (A) and area-specific sediment yield (SSY) for Spain and Italy. Reservoir sedimentation data for both are significantly ($p = 0.0001$) higher than erosion rates measured in plots. Source: The Spanish example is adapted from de Vente and Poesen (2005).

de Vente and Poesen (2005). The Italian and Spanish examples show clearly that average erosion rates measured in plots are significantly lower than the sediment yield measured in reservoirs at the basin scale, an observation that was also reported by Poesen and Hooke (1997) and García Ruiz *et al.* (2004) comparing plot data and reservoir data

in Spain. Moving from the plot scale to larger areas, the examples in Figure 4 show an increase in SSY . In the Spanish example, the effect of substantial sediment deposition and reduced average erosion rates becomes notable from a basin area of about 1 km^2 when SSY starts to decrease with increasing A . In the Italian example, however, a slightly positive (though not significant) relation is maintained also at larger scales. This is most probably explained by the relatively better-developed vegetation cover in Italy as compared to Spain and by the important role of channel erosion and landslides for SSY in the Italian basins (de Vente *et al.*, 2006).

The scale dependency of SSY and the importance of gully erosion for the sediment budget were also demonstrated in a study in the Belgian Loess belt (Vanwalleghe *et al.*, 2005). In this study, data from runoff plot measurements were combined with volumetric gully measurements and pond sedimentation data (see Figure 5C). The results show that, going from the plot scale to larger areas, SSY increases due to the development of (ephemeral) gullies. SSY starts to decrease with increasing A beyond a basin area of about 0.04 km^2 due to deposition of sediments during transport. Furthermore, it is demonstrated that, when only shallow ephemeral gullies are present, the rise in SSY is much less pronounced than when deep gullies also develop in the basin. Deep gullies were defined by a depth at the gully head of more than 0.8 m .

Beside basin area, topographic thresholds also play an important role for the initiation of different erosion processes. For example, various authors reported a clear relation between slope gradient and upslope area for gully initiation (eg, Montgomery and Dietrich, 1994; Desmet *et al.*, 1999; Vandekerckhove *et al.*, 2000; Poesen *et al.*, 2003). So, spatial differences in topography may cause SSY to increase or decrease independent of A .

At the scale of large drainage basins, another important scale effect was reported by some authors. Based on data from British Columbia (Canada), Church and Slaymaker

Figure 5 Various examples of a complex relation between drainage basin area (A) and area-specific sediment yield (SSY)

Source: Relations are redrawn from various publications.

(1989) reported an increasing SSY until a basin area of approximately $3 \times 10^4 \text{ km}^2$, while for larger drainage basins SSY decreased with increasing A (see Figure 5D). The increase in SSY was explained by the remobilization of glacial deposits mainly by channel erosion

processes. The decrease in SSY at a larger drainage basin size was explained by the presence of relatively wide valleys with well developed floodplains which protect non-alluvial banks from bank erosion and reduce the intensity of sediment remobilization

Table 2 Summary of soil erosion rates measured in Italian erosion plots (see also Figure 4)

Area (m ²)	SSY (t km ⁻² y ⁻¹)	Mean SSY (t km ⁻² y ⁻¹)	Land-cover type	Reference
20	22	28	Public woodland	(Vacca <i>et al.</i> , 1994)
20	19		Shrubs after fire	"
20	43		Eucalyptus stand	"
100	26	25	Fertilized pasture	(Porqueddu and Roggero, 1994)
100	23		Fertilized pasture burnt at end of season	"
100	243		Annual forage crop (rye grass and berseem clover)	(Porqueddu and Roggero, 1994)
100	496	2	Ploughed bare field	"
100	5		permanent natural pasture	(Careda <i>et al.</i> , 1997)
100	67		Improved pasture	"
100	25		Forage crop (oats, vetch and Persian clover)	"
100	17		Grain oats	"
100	5		Ploughed fields	(Rivoira <i>et al.</i> , 1989)
100	5		Cash crop	"
100	3		Natural pasture	(Rivoira <i>et al.</i> , 1989)
100	1		Shrub cleared pasture	"
100	3		Pasture cleared by fire	"
100	2		Pasture with shrubs	"
600	135	158	Durum wheat, direct drilling	(Basso <i>et al.</i> , 2002)
600	173		Durum wheat, direct drilling	"
600	415		Horse bean, direct drilling	"
600	123		Durum wheat, rotavation	"
600	163		Durum wheat, rotavation	"
600	39		Durum wheat, rotavation	"
600	327		Horse bean, rotavation	"
600	76		Horse bean, rotavation	"
600	117		Durum wheat, ploughed to 20 cm	"
600	159		Durum wheat, ploughed to 20 cm	"
600	366		Horse bean, ploughed to 20 cm	"
600	112		Durum wheat, ploughed to 40 cm	"
600	158		Durum wheat, ploughed to 40 cm	"
600	55		Durum wheat, ploughed to 40 cm	"
600	388		Horse bean, ploughed to 40 cm	"
600	91		Horse bean, ploughed to 40 cm	"
600	41		Durum wheat, scarifying at 50 cm	"
600	73		Horse bean, scarifying at 50 cm	"
600	48		Durum wheat, scarify at 50 and ploughed at 40 cm	"
600	92		Horse bean, scarify at 50 and ploughed at 40 cm	"
1000	125		Tillage following contours	(Basso <i>et al.</i> , 2002)

(Continued)

Table 2 Continued

Area (m ²)	SSY (t km ⁻² y ⁻¹)	Mean SSY (t km ⁻² y ⁻¹)	Land-cover type	Reference
1000	154		Tillage following slope	(Basso <i>et al.</i> , 2002)
1000	203		Horse bean	"
1000	166		Durum wheat	"
1000	156		Sweet vetch	"
1000	123		Mixed hay field (with alfalfa)	"
1000	61	141	Natural pasture	"

(Church and Slaymaker, 1989; Schiefer *et al.*, 2001). Besides, at larger drainage basin size, drainage density will generally decrease, which will reduce the input of sediment from bank erosion per unit of area.

Another example of scale effects on SSY in large basins was provided in a case study of SSY in the Yellow River (China). Here, it was demonstrated that a change in active erosion processes and a change in SSY can be provoked by important spatial differences in lithology and vegetation cover (Jiongxin and Yunxia, 2005), slope gradient and (gully) drainage density (Fang *et al.*, 2006). In the case of the Yellow River, the highest SSY values were measured in the middle part of the basin at a basin area of approximately 2000 km². Both upstream and downstream of this point SSY decreased (see Figure 5E). The explanation for this phenomenon is that erosion rates are generally much higher in the central Loess plateau, where highly erodible Loess deposits can reach up to 200 m thickness, than in the other areas where surface material consists of either Aeolian sands or bedrock. In the Loess area, deep gully formation, channel erosion and mass movements are responsible for high erosion rates and a well-developed sediment connectivity with the river channel, resulting in a high SSY (Jiongxin and Yunxia, 2005). Fang *et al.* (2006) showed for tributaries of the Yellow river within the Loess plateau that actually various peaks in SSY can be observed for drainage basin from 0.0006 to 3993 km².

A first peak at an area of 0.004 km² was related to an increased slope gradient and the development of a rill and gully network. The development of a dense (gully) drainage network at an area of almost 100 km² caused a second peak in SSY.

The previous examples focused mainly on the scale effect from the plot to the large basin scale ($\sim 10^{-5}$ – 10^6 km²). However, various studies accentuated the scale dependency of soil erosion rates and sediment yield from the plot to the small catchment scale ($\sim 10^{-5}$ – 10^{-1} km²). In a review of erosion plot measurements in Spain, Boix-Fayos *et al.* (2007) reported an increase in sediment yield going from small plots to a small catchment (ie, 1–78,600 m²). They emphasized the large variation that is found between plot measurements at different scales and between replica plots. They explained this variation by the fact that different erosion processes are active at different spatial scales and by variation in the spatial pattern of soil surface characteristics (ie, stoniness, crusts, vegetation pattern) between plots. The spatial pattern of surface characteristics influences runoff distance and connectivity on a hillslope. This often results in a patchy pattern of runoff and runoff sites and a discontinuity of flow (Bergkamp, 1998; Calvo-Cases *et al.*, 2003; Boix-Fayos *et al.*, 2006). This makes that SSY can either increase or decrease going from the plot to the small catchment scale (eg, Le Bissonnais *et al.*, 1998; Chaplot and Le Bissonnais, 2000; Parsons *et al.*, 2006a;

Boix-Fayos *et al.*, 2007). This is in agreement with Parsons *et al.* (2004), who suggested a conceptual model to determine erosion rates and sediment fluxes in which sediment transport depends strongly on travel distance. In their model the sediment flux due to interrill erosion increases in the first metres of a slope after which the flux gradually decreases. This trend was confirmed by plot measurements varying in length between 2 and almost 30 metres (Parsons *et al.*, 2006a), and by the results of Evans (1995) who found that measured erosion rates at the field scale become smaller with increasing area of measurement due to increasing travel distance. In contrast, in the model of Parsons *et al.* (2004) the sediment flux originating from rill and gully erosion continuously increases with distance downslope (Parsons *et al.*, 2004). Therefore, for relatively small areas where gully erosion is not the dominant erosion process, SSY may increase or decrease with increasing A . However, when gully erosion is prevailing, SSY will increase with increasing A , as was also illustrated by the examples from Spain, Italy and Belgium (see Figures 4 and 5C).

The importance of sediment travel distance and active erosion processes for SSY estimates was also illustrated by the analysis of sediment yield measurements in agricultural uplands of Indonesia (van Dijk and Bruijnzeel, 2005). In downslope direction first a decrease, then a rise, and then a continuous decrease in SSY with increasing distance downslope was found. This trend was explained by a shift from splash and sheet erosion to rill and gully erosion as the dominant erosion process. Transport distances in the domain of splash and sheet erosion were generally short due to infiltration of runoff and discontinuity of flow. Only when sufficient concentration of flow occurred in rills and gullies did SSY start to increase with increasing distance downslope. The ultimate decrease in SSY was explained by deposition and reduced erosion rates due to a decrease in slope gradient (van Dijk and Bruijnzeel, 2005).

V Discussion

1 Conceptual models of the basin area – sediment yield relation

Although the previous examples show that the relation between basin area (A) and area-specific sediment yield (SSY) is not straightforward, interpretation of the relation can help to understand sediment yield dynamics and to identify the most important sediment delivering processes at different spatial scales. Figure 6 conceptualizes three typical trends between A and SSY that can be identified based on the examples presented in this paper. An explanation for each trend and some examples from literature are provided as well. Figure 6A is illustrative for the scale dependency of erosion and sediment deposition processes. Figure 6B represents the dependency of dominant erosion processes on land use and human impact, while Figure 6C illustrates how spatial patterns of land use, climate, lithology and topography can dictate the trend between A and SSY. From these examples it is clear that no uniform relation between A and SSY is to be expected along all spatial scales but rather that the trend depends on scale, dominant erosion processes and on spatial patterns of lithology, topography, climate and land use within the drainage basin. Furthermore, the examples illustrate that the trend is not always constant in time.

First of all, an important explanation for spatial differences in SSY results from the fact that with increasing A more erosion and sediment transport processes will operate, from splash erosion, sheet erosion, to rill, gully, bank erosion and mass movements (Osterkamp and Toy, 1997; de Vente and Poesen, 2005). The importance of these processes depends on spatial scale and on topographic thresholds, but is also influenced by the spatial configuration of land use, topography and lithology. In many Mediterranean regions, for instance, moving from the mountain uplands, consisting of relatively well-vegetated hard rock formations

Figure 6 Three typical trends between basin area (A) and area-specific sediment yield (SSY) based on the examples presented in this paper with explanations for differences and examples of observed trends

(eg, forest on limestone or sandstone) to intensely cultivated intramontane basins with unconsolidated sediments (eg, marls), erosion rates, sediment transport capacity and SSY increase with increasing A . Therefore, it seems plausible that moving from a small spatial unit ($< \text{m}^2$) to larger areas (km^2) there will always be an overall increase in mean annual SSY, irrespective of the trend at larger spatial scales (Figure 6, A, B, C). For small areas ($< \sim 0.01 \text{ km}^2$) the increase may be irregular due to discontinuity of flow, a lack of sediment connectivity and spatial variability of surface conditions (eg, vegetation, rock fragment cover, crusts). However, as soon as gullies develop, sediment connectivity will increase and so SSY will also increase with increasing A (Poesen *et al.*, 2003). This is also in agreement with Renschler and Harbor (2002) who presented a conceptual model where active erosion processes (splash, sheet, rill, gully, fluvial erosion) were related to spatial and temporal scale and to specific soil (texture, structure, moisture content), vegetation (grass, canopy, buffer strips), and climate characteristics (breeze, thunderstorm, front, El Niño).

Beside the thresholds of A and topography to initiate erosion processes, land cover has an important influence on the dominant active erosion processes in a basin. In basins intensively impacted by agricultural use, hillslope erosion (splash, sheet, rill and ephemeral gully erosion) is often dominant over river channel erosion processes. For sufficiently large A ($> \sim \text{km}^2$), SSY from hillslope erosion typically decreases with increasing A due to decreasing slope gradients downstream and the presence of sediment sinks at field boundaries, slope concavities and in floodplains (Walling, 1983; Dedkov and Moszherin, 1992; Osterkamp and Toy, 1997; Church *et al.*, 1999; Slaymaker *et al.*, 2003; Dedkov, 2004). This results in the overall trend as shown in Figure 6A.

On the other hand, in basins with limited human impact and a well-developed vegetation cover, hillslope erosion will not have a

significant contribution to sediment yield. In these basins sediment yield is controlled by permanent gully and river channel erosion processes and possibly by landslides (Dedkov and Moszherin, 1992; Church *et al.*, 1999; Slaymaker *et al.*, 2003; Dedkov, 2004). This results in a continuous increase in SSY with increasing A since channel erosion shows limited deposition losses during transport. The presence of large volumes of unconsolidated sediments close to river channels forms an easily erodible source of sediments and so will strengthen the positive relation. Only for very large ($> \sim 10^4 \text{ km}^2$) drainage basins it is expected that SSY will decrease due to widening of valleys and a general decrease in drainage density causing less input of sediment per unit area (Figure 6B).

Interesting to note is that the maximum SSY for the basins in Figure 3 is lower than the maximum SSY of basins in Figure 2. The explanation for this might be that basins with a positive relation between A and SSY are generally characterized by a well-developed vegetation cover and so erosion rates in general will be lower than in disturbed and intensively cultivated catchments that often show a decrease in SSY with increasing A .

The previous parts discussed the importance of spatial scale and regional land-use characteristics for sources and sinks of sediment. Obviously, the spatial configuration of land use, lithology, climate, and topography will also control the spatial distribution of sources and sinks of sediment, and therefore the trend between A and SSY. Various examples in this paper illustrated that a rise in SSY can actually occur at any spatial scale due to local or regional conditions favourable to erosion and sediment transport (Figure 6C). A clear example is the Yellow River (China) where SSY strongly increases when entering the Loess belt, and decreases again when erosion rates are reduced outside of the Loess belt (Jiongxin and Yunxia, 2005; Fang *et al.*, 2006). The model simulations with SHETRAN (Birkinshaw and Bathurst, 2006), the model results of Lu *et al.* (2005),

and the SSY data from Costa Rica (Krishnaswamy *et al.*, 2001) also illustrate that the spatial pattern of land use, climate and lithology can cause SSY to increase at any spatial scale. The example from British Columbia (Church and Slaymaker, 1989) demonstrates that SSY can increase until very large drainage basin sizes and is constrained by geomorphologic conditions such as channel width and floodplain development.

The conceptual model presented in Figure 6 should be interpreted qualitatively rather than quantitatively, since the exact values of SSY and A will change with local conditions in each basin. Not all erosion and sediment transport processes are equally important in all basins, which may cause the trends to be more pronounced or flattened. The basin area for which maximum SSY is observed, the A-threshold from which SSY starts to decrease, as well as the magnitude of SSY in general, depend on environmental factors such as climate, land use, topography and lithology. Nevertheless, the relative trends for the conditions discussed above are expected to be valid.

2 Human impact and long-term sediment yield

As explained before, it seems reasonable to assume that in basins with important human impact different erosion processes are responsible for the main part of sediment yield than in basins with limited human impact. In some cases this is also reflected in a significant increase (ie, between 2 and 200 times) in total sediment yield following human impact (eg, Einsele and Hinderer, 1997), or in a decrease after implementation of conservation measures (eg, Renwick and Andereck, 2006). However, often there is no clear response, or a delay between the moment of human impact and a related change in sediment yield leaving the basin. The absent or delayed response can be explained by a change in active erosion processes (upland versus channel erosion) and by the buffer capacity of a basin (ie, storage in sediment

sinks). Nevertheless, over millennial timescales it is expected that all sediments will be transported out of a river basin, resulting in a Sediment Delivery Ratio (SDR) close to 100% (Lu *et al.*, 2005). This is also insinuated by the absence of a relation between A and SSY for measured long-term erosion rates (eg, Kirchner *et al.*, 2001; Schaller *et al.*, 2001). On the other hand, the Canadian example (Church and Slaymaker, 1989) illustrates that it may take more than several tens of thousands of years for a landscape to respond to perturbations and export all sediments from a basin. So, in fact the SDR is a function of the timescale over which erosion rates and sediment yields are measured (Lu *et al.*, 2005). Over long periods of geologic time the SDR should approach unity but for shorter periods storage or flushing of sediments will predominate, and so the SDR can be much smaller or even larger than 100% (Schumm *et al.*, 1976; Lu *et al.*, 2005). Furthermore, changes in climate, land cover and tectonics will disturb drainage basin evolution and make the occurrence of a SDR of 100% unlikely for most basins at any given period in time (Schumm *et al.*, 1976).

The importance of time is also illustrated in a study of reservoir sedimentation rates in Ohio (USA), where an important change in the A-SSY relation was found between measurements pre-1960 and those in the second half of the twentieth century (Renwick and Andereck, 2006). Before 1960 dominant agricultural use caused high erosion rates and significant alluvial deposition reflected in a clear negative trend between A and SSY, and a SDR lower than 100%. In contrast, in the second half of the century agricultural erosion declined resulting in decreasing sedimentation rates, but also in an important flattening of the A-SSY relation, which might imply that channels shift from sediment sinks to neutral conditions or even sediment sources (Renwick and Andereck, 2006). Conversely, various other studies demonstrated that changes in land use caused significant changes in sediment dynamics within a drainage basin,

without causing important change in total sediment yield (eg, Trimble, 1999; Walling, 1999; Prosser *et al.*, 2001). This means that in basins with a recent human impact sediment yield can still reflect conditions from before the human impact, or the other way around, ie, the effect of soil conservation measures may not be noticed until long after they have been implemented (eg, Trimble, 1975; 1999; Trimble and Lund, 1982). These examples are in agreement with Schumm (Schumm *et al.*, 1976; Schumm, 1977) who emphasized that sediment yield often shows a complex response to periods of intense upland erosion and does not necessarily reflect contemporary upland erosion rates. Furthermore, this illustrates that the relation between A and SSY is not necessarily constant in time and its interpretation in relation to human impact and changing land-cover conditions or climate should therefore be done carefully.

3 Methodological constraints and prediction of sediment yield

Part of the variation in SSY data reported in literature is due to differences in methodologies used to collect the data. Some of the data presented here were obtained by suspended sediment yield sampling and others by bathymetric reservoir surveys. Reservoir surveys are generally seen as producing more reliable results than suspended sediment measurements since the latter do not include bedload and often represent only short periods of measurement, which implies that the effect of extreme events is not always represented in the data. In contrast, reservoir data do include bedload and often represent longer time periods (>10 yr) of sediment yield including also more extreme events. Therefore, it is evident that the different methodologies will cause additional variation in sediment yield that cannot be attributed to basin area or other basin characteristics.

Although the concept of a Sediment Delivery Ratio (SDR) can help to characterize sediment dynamics and drainage basin evolution, the assessment of an SDR is troublesome.

First of all, calculation of an SDR according to equation 2 requires assessment of gross erosion, which is often done by some empirical or physical prediction equation, and is subject to serious uncertainty (Walling, 1983; Trimble and Crosson, 2000). A large part of this uncertainty comes from the inability to include the effect of gully erosion, bank erosion and landslides in the equations. Moreover, the estimate of gross erosion is dependent on an arbitrary distance of movement of soil particles over the time period of measurement. The choice of these arbitrary spatial and temporal scales significantly affects the computed value for gross erosion (Parsons *et al.*, 2006b). Furthermore, the often assumed analogy between the slope of the 'A-SSY' relation and the 'A-SDR' relation suggests that gross erosion rates are spatially uniform within a basin, which is obviously not the case for many basins. A negative relation between A and the SDR can still result in a positive or unclear relation between A and SSY when gross erosion increases strongly across spatial scales, as is the case for example in the basin of the Yellow River (Jiongxin and Yunxia, 2005). Furthermore, the negative relation between A and the SDR reflects mainly the effect of deposition during transport of soil eroded on hillslopes by sheet, rill and ephemeral gully erosion. In contrast, often only a small part of the material eroded by river channel erosion will be deposited during transport downstream. Therefore, as sediment transport characteristics and erosion rates are not spatially uniform, the relation between A and the SDR will not necessarily be analogous to the relation between A and SSY. Parsons *et al.* (2006b) even go a step further and question the concept of sediment delivery based on sediment yield per unit area. They state that only a small part of a basin will contribute to sediment yield, and therefore it is better to present sediment fluxes in mass per unit time (t yr^{-1}), rather than area-specific sediment yield ($\text{t km}^{-2} \text{ yr}^{-1}$). Although it is certainly true that the source area of sediment yield is not evenly distributed

over a basin, the current study illustrates that the analysis of A–SSY relations provides important information on erosion and sediment delivery processes operating within the basin. Or, as Lu *et al.* (2005) stated it, the SDR may be more an indicator of the relative contribution of channel versus hillslope erosion than of the upland sediment delivery efficiency.

VI Conclusions

The examples presented in this paper illustrate that the relation between basin area (A) and area-specific sediment yield (SSY) shows large regional variation. Overall, there is a tendency for SSY to decrease with increasing A, but there is a very large variation in SSY for basins of the same basin area of up to four orders of magnitude. Furthermore, regional stratification of the data shows that negative, positive and complex relations between A and SSY occur. This leads to the conclusion that A explains only a small part of the variation in sediment transfer processes and is a poor predictor of SSY.

The conceptual model presented in this paper summarizes explanations for the differences in the observed trends between A and SSY. This model emphasizes that the dominance of specific erosion processes (ie, splash, sheet, rill, gully, mass wasting) controls the relation between A and SSY. First of all, these erosion processes depend on spatial scale. Moving from small (<1 km²) to larger areas (km²), basin area thresholds beyond which erosion processes become dominant make that SSY increases with A. For larger areas and larger sediment transport distances, SSY generally decreases due to sediment deposition in sinks and reducing erosion rates. Secondly, erosion processes depend on land-cover conditions. In basins intensively disturbed by agricultural use it is likely that hillslope erosion is dominant over channel erosion, which results in a decreasing trend between A and SSY. Conversely, in basins with limited human impact and a well-developed vegetation cover, channel erosion dominates

over hillslope erosion, and so SSY will continuously increase with increasing A, until valleys become wider, drainage density decreases and river banks become stabilized. These trends between A and SSY can, however, be disturbed at any spatial scale due to distinct spatial differences in soil erodibility, rainfall characteristics, land use or topography within the basin, resulting in an increase or decrease in SSY independent of A. Furthermore, temporal variation in the susceptibility to erosion and sediment transport may cause the A–SSY relation to change over time.

Altogether, the observed regional and local variation in the relation between A and SSY has important implications for modelling and prediction of SSY using this relation. First of all, sediment yield measured at one scale (ie, plot, hillslope, catchment, region) cannot simply be extrapolated to another scale level. Furthermore, the application of a uniform relation between A and SSY or of a uniform SDR over large regions or even worldwide is not recommendable. Instead, for prediction purposes it is preferable to use spatially distributed information on land use, climate, lithology and topography, and be aware of the history of human impact and geomorphic development. It is also important to realize at what scale the model is applied, which are the dominant erosion processes, what is the dominant land use, and how spatial patterns of these factors constrain erosion and sediment transport at the basin scale. Even with all this information available, it still remains difficult to predict sediment yield, but it may help to better understand the problem of sediment delivery.

Acknowledgements

The SENECA foundation in Spain is kindly acknowledged for financial support to the first author. We would also like to express our thanks to the CEBAS-CSIC (Murcia) and the colleagues of the Soil and Water Conservation Department for their help and hospitality.

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