Sediment yield in Europe: regional differences in scale dependence

MATTHIAS VANMAERCKE[1], JEAN POESEN[1], GERT VERSTRAETEN[1], WILLEM MAETENS[1], JORIS DE VENTE[2] & FARUK OCAKOGLU[3]

1 *Physical and Regional Geography Research Group – K U Leuven, Celestijnenlaan 200E, 3001 Heverlee, Belgium*
matthias.vanmaercke@ees.kuleuven.be

2 *Estación Experimental de Zonas Áridas, EEZA-CSIC, Desertification and Geoecology Department, Almeria, Spain*

3 *Eskişehir Osmangazi University, Department of Geological Engineering, Eskişehir, Turkey*

Abstract Current understanding of the regional variation in sediment yield (SY) and its scale dependence is limited for Europe. Based on an extensive literature review, a SY-database was assembled to bridge this gap. Measured SY-data from 1794 different locations throughout Europe were collected, representing a minimum of 29 203 catchment-years of records and comprising a wide range of catchment areas (0.01 km^2 to 1 360 000 km^2). Clear differences were observed between the temperate regions of Europe (low SY-values, i.e. <50 t km^{-2} year^{-1}) and the Mediterranean and mountainous regions of Europe where SY-values are generally higher (i.e. >300 t km^{-2} year^{-1}). Furthermore, for most temperate regions a negative relationship was found between catchment area and SY. For mountainous and Mediterranean regions, this was generally not the case. A comparison of catchment SY with rates of sheet and rill erosion also points to clear regional differences. Whereas soil erosion rates are generally higher than SY for temperate regions, this is not the case for the Mediterranean region. This indicates the importance of other erosion processes (i.e. landslides, riverbank erosion, and gullies). The results illustrate important regional differences in the scale dependence of SY and emphasize the need for an integrated modelling approach considering various types of sediment source and sink.

Key words sediment yield; database; Europe; erosion; scale-dependence; sheet and rill erosion

INTRODUCTION

Soil erosion by water has received considerable attention in Europe (e.g. Boardman & Poesen, 2006). Extensive research during the last decades has led to an improved understanding of the spatial patterns and intensity of water erosion processes at the hillslope scale in Europe (e.g. Kirkby *et al*., 2004; Cerdan *et al*., 2006). Current understanding of sediment export rates at the catchment scale is, however, much more limited. Nevertheless, an improved understanding is a critical requirement for controlling the off-site impacts of soil erosion, including, for example, reservoir siltation (Verstraeten *et al*., 2006) and eutrophication (Rekolainen *et al*., 2006).

Several studies have indicated that extrapolation of soil erosion rates from the hillslope to the catchment scale is not straightforward, as with increasing catchment area other erosion and sediment deposition processes become more important (Walling, 1983; de Vente & Poesen, 2005; de Vente *et al*., 2007). Attempts to model sediment yield (SY, t km^{-2} year^{-1}) at the catchment scale in a physical way often perform badly as they do not include all relevant erosion and sediment deposition processes, or there are excessive data requirements (Merritt *et al*., 2003; de Vente & Poesen, 2005). Empirical models are therefore a powerful alternative, as they have smaller data requirements and often perform at least equally well (Jetten & Favis-Mortlock, 2006). However, their results are only valid for either large river systems at a global scale (e.g. Syvitski & Milliman, 2007) or for a specific region (e.g. Aalto *et al*., 2006; de Vente *et al*., 2006, 2008; Verstraeten, 2006) and depend heavily on their calibration, due to site-specific conditions. Hence, our understanding of regional differences in sediment yields, their controlling factors and their scale dependence are currently limited for the European continent.

An important issue, hampering a better understanding of the spatial variations of SY in Europe, is the lack of a synthesis of available sediment yield data. Nevertheless, many sediment yield data exist for European catchments, reported in various scattered sources. Although several authors have summarized available sediment yield data worldwide, they do not exploit the full potential of the currently available SY-data for Europe as they only consider larger river systems (i.e. >100 km^2) and include only a limited number of catchments for Europe. (e.g. Jansson, 1988: 445 entries for Europe; Meybeck & Ragu, 1995: 45 entries; Milliman *et al*., 1995: 112 entries). Furthermore, many new SY-data have been published recently.

The objectives of this study are to: (i) present an overview of available SY-data in Europe, collected from different sources; (ii) discuss differences in SY for different regions in Europe; and (iii) explore regional differences in the scale dependence of SY in Europe.

CONSTRUCTION OF THE DATABASE

Based on an extensive literature review, data on sediment yield of European rivers were collected from scientific publications, MSc and PhD theses, and reports from hydrological institutes. Only sediment yield data derived from measurements at a gauging station or from reservoir siltation rates, over a measuring period of at least one year, and for a catchment area (A, km^2) of at least 0.01 km^2, were considered.

Each entry in the database corresponds to one catchment for which SY has been measured and contains at least the name of the river, the measurement method (observation at a gauging station (GS) or derived from a reservoir siltation rate (R)), the location of the GS or R, A (km^2), the total sediment yield (TSY, t year^{-1}), the area-specific sediment yield (SY, t km^{-2} year^{-1}), and the measuring period. For several entries, the actual measuring period was not reported, but was indicated to be longer than one year. In these cases, a measuring period of one year was assumed. If available, additional information on the measuring method was also recorded. The coordinates of all entries were included, based on the originally reported coordinates. If original coordinates were unavailable, an estimate was made, based on the description of the measuring location, using Google Earth™. If the measuring location could not be determined with sufficient accuracy (e.g. when no location name was reported), the entry was not included in the database. As many SY data are reported several times in different sources, the database was checked for duplicate entries. Two entries were considered as duplicates if they had the same measuring location and (therefore) the same drainage area. In such cases, only the most reliable entry was used. In general, the source that reported the sediment yield for the longest measuring period was considered as most reliable. If the measuring periods were equal or unknown, the source that provided the most detailed information on the measuring location and measuring technique was used.

The GS-entries in the database comprise SY-data measured and calculated by a wide variety of techniques and procedures. It was assumed, however, that all reported sediment export rates, were estimated as accurately as possible, and all sediment export values were incorporated in the database as reported in their original reference. For GS-entries, only the suspended sediment export was considered, because bedload data were unavailable for most gauging stations and dissolved loads fell outside the scope of this study. For R-entries, TSY was estimated as the product of the annual sedimentation rate in the reservoir or pond (m^3 year^{-1}) and the dry sediment bulk density (dBD, t m^{-3}), divided by the sediment trap efficiency of the pond or reservoir (TE). In several cases, values were not available for all the factors in this calculation. Some sources did not report the dBD of the sediment. In these cases, a bulk density of 1.12 t m^{-3} was assumed. This value was calculated as the average bulk density of a large data set of reservoir siltation rates (Verstraeten *et al*., 2006). Also, TE was unknown in most cases. Although TE can be measured, this is generally expensive and time-consuming. Several procedures exist to estimate TE (Verstraeten & Poesen, 2000). In our study, missing TE-values were estimated using an empirical equation where TE is assessed based on the reservoir capacity, the catchment area, and a constant depending on specific characteristics of the reservoir (Brown, 1943, in Verstraeten & Poesen, 2000).

DESCRIPTION OF THE DATABASE

The constructed data set currently consists of 507 R-entries and 1287 GS-entries. The sum of the duration of the measuring periods of all the R-entries represents a minimum of 13 751 “catchment years" of data (for 87 R-entries the measuring period was unknown and a period of 1 year was assumed). The GS-entries cover a minimum of 15 452 catchment years of data (for 120 GS-entries a period of 1 year was assigned as the measuring period was unknown). Table 1 gives an overview of the number of entries and the number of catchment years for the different climatic zones of Europe (according to the LANMAP 2 classification; Metzger *et al.*, 2005; Mücher *et al.*, 2006). Figure 1 displays the climatic classification used. The climatic zone of each entry was determined,

Table 1 Overview of the number of entries compiled in the SY-database, per climatic region (see Fig. 1).

Climatic zone	# GS-Entries	Catchment years	# R-Entries	Catchment years	Total # Entries	Catchment years
Atlantic	191	939	91	4729	282	5668
Boreal	85	1060	8	429	93	1489
Continental	463	7066	145	2091	608	9157
Arctic	7	26	-	-	7	26
Mediterranean	356	3988	184	4966	540	8954
Steppic	25	231	12	228	37	459
Anatolian	62	1175	8	8	70	1183
Alpine	98	967	59	1300	157	2267
All data	1287	15452	507	13751	1794	29203

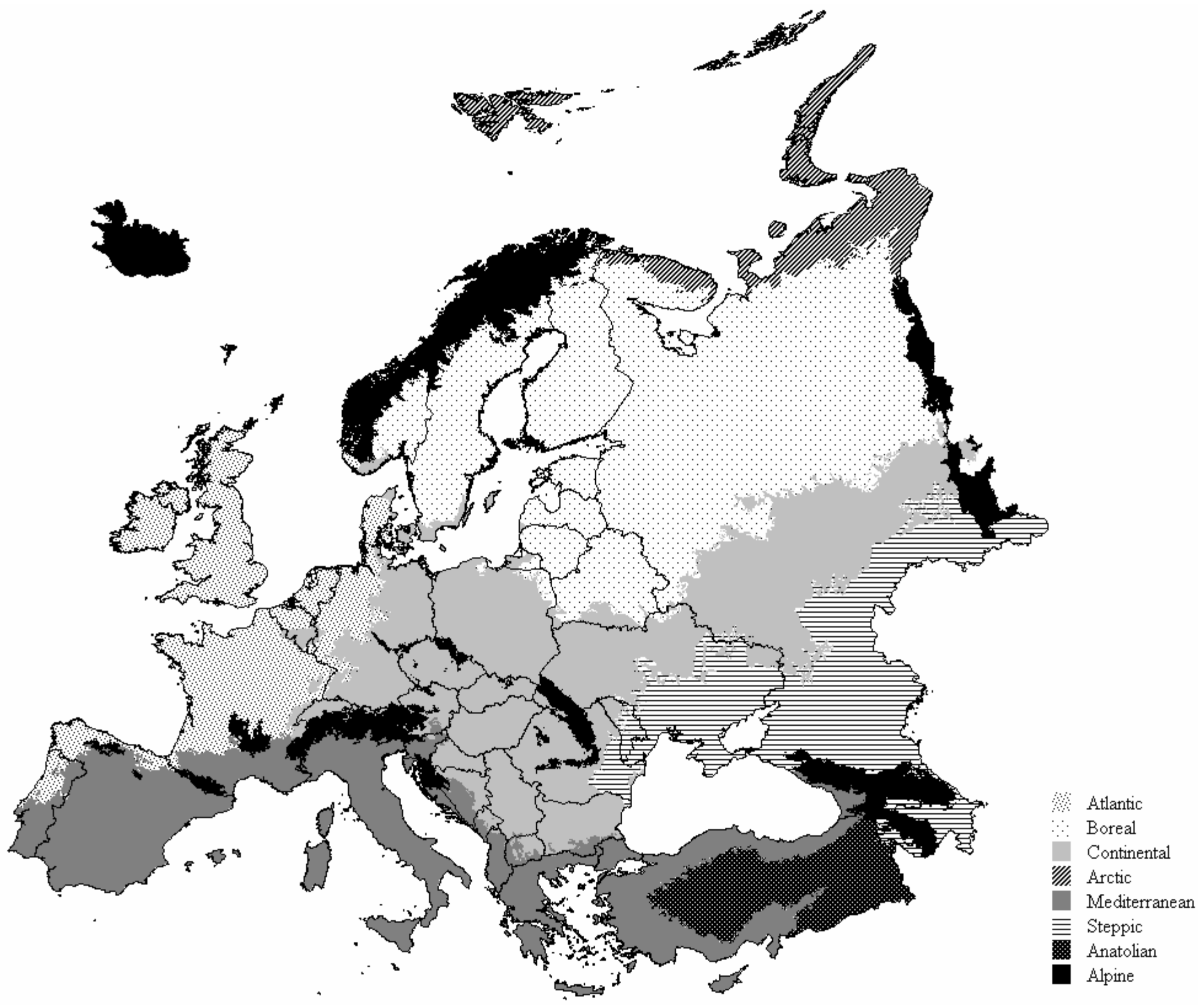

Fig. 1 Climatic division of Europe according to the LANMAP 2 classification (Mücher *et al.*, 2006; Metzger *et al.*, 2005).

based on the location of the GS or R. As some large catchments cover more than one climatic zone, their assignment to the climatic zone of the outlet may be questioned. However, the number of catchments in the database having this situation is expected to be relatively small (i.e. <25%).

Whereas several regions are represented by many SY-data (e.g. Romania, Italy, Spain, Turkey), for other areas only a limited number of entries or no data at all (e.g. Ireland, Belarus, Lithuania) were found. For several countries, more SY-data exist, but they could not be obtained (e.g. Ukraine; Kovalchuk & Vishnevskiy, 2004). The synthesis presented here is therefore not a full synthesis of all SY-data, but covers the vast majority of available SY-data in Europe.

Figure 2 shows the distribution of all entries and number of catchment years according to their drainage area. From the histogram, it is clear that most entries have drainage areas of between 100 and 10 000 km^2. Data from catchments smaller than 10 km^2, and especially smaller than 1 km^2, are relatively rare. The distribution of the number of catchment years per A-class corresponds more or less with the distribution of the number of entries, except for entries with a catchment area of 1–10 km^2. This group has a relatively larger number of catchment years as it includes several old reservoirs in England from which long-term SY-values could be calculated. A more detailed description of the data and their sources is provided in Vanmaercke *et al*. (2010).

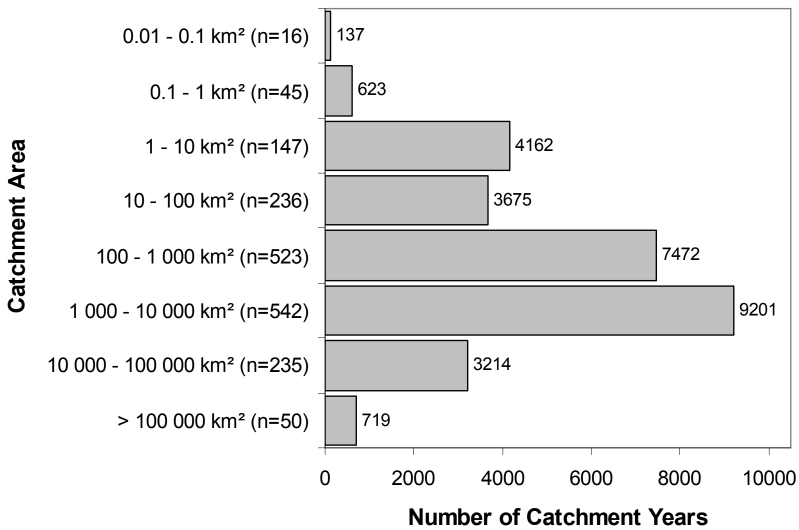

Fig. 2 Overview of number of catchment-year data in the database for several catchment area classes (n indicates the corresponding number of entries).

SPATIAL PATTERNS AND SCALE DEPENDENCE OF SY IN EUROPE

The range of measured SY-values per climatic zone is shown in Table 2. Large differences in SY exist both between and within these regions. Although direct interpretation is difficult, because the SY-data involved were collected from a wide range of catchments using different measuring techniques, Table 2 suggests that catchments in the Mediterranean and Alpine climatic zones are characterized by high SY-values, whereas catchments in the Boreal and Atlantic climatic zones generally have lower SY-values. Statistical analysis of the data confirms this.

Figure 3 displays the results of regression of SY against A for the different climatic zones. The low r^2 values associated with these regressions can be explained by the importance of other factors controlling SY. Each climatic zone covers a large area with a large variation in physical factors such as topography, lithology and land use. Furthermore, the SY-data used for the regressions incorporate differences in measuring method and measurement period. Nevertheless, contrasts can be observed between the climatic zones. Whereas the Atlantic, Boreal and Continental zones have weak but significant (α = 0.05) negative relationships with comparable slopes and r^2-values, this is not the case for the Anatolian and Alpine climatic zones, which show

Table 2 Statistical characteristics of the sediment yield (SY, t km^{-2} year^{-1}) and drainage area (A, km²) values per climatic zone (see Fig. 1).

Climatic zone	min SY *min A*	median SY *median A*	mean SY *mean A*	max SY *max A*	Std SY *Std. A*
Atlantic	0.4	28	100	2834	243
	0.1	*135*	*10199*	*163896*	*27764*
Boreal	0.5	6	40	1256	141
	0.1	*2054*	*17356*	*229000*	*36281*
Continental	0.5	70	177	4678	338
	0.04	*1147*	*19668*	*1280000*	*92648*
Arctic	27.9	98	148	359	126
	0.7	*7*	*15*	*33*	*15*
Mediterranean	0.3	218	673	30000	1863
	0.01	*722*	*5189*	*97800*	*14197*
Steppic	1.8	60	281	1980	419
	48.0	*9700*	*165574*	*1360000*	*330504*
Anatolian	1.4	144	366	4299	683
	43.5	*3417*	*6343*	*36642*	*8352*
Alpine	0.9	198	451	8990	876
	0.3	*203*	*764*	*10550*	*1480*
All data	0.3	92	341	30000	1113
	0.01	*791*	*14460*	*1360000*	*76683*

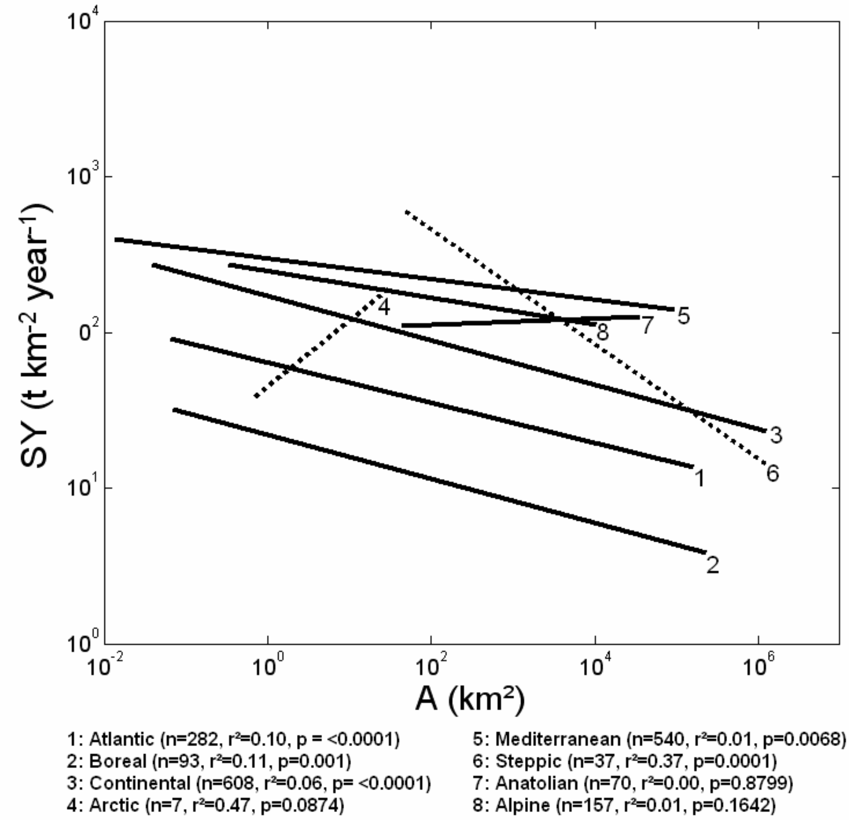

Fig. 3 Sediment yield (SY) – catchment area relationships for individual climatic zones (see Fig. 1). (n = number of data points used to derive each relationship, r² = coefficient of determination, p = F-statistic probability).

no significant relationship. The Mediterranean zone has a significant A–SY relationship, but the slope and r^2 of this relationship are considerably lower than those for the other zones with significant relationships. Moreover, it was found that this relationship was strongly influenced by six small catchments (A < 0.1 km^2) with a very high SY. If these catchments are left out, the relationship is no longer significant. For the Steppic zone, a significant negative relationship was found. This trend is, however, based on a relatively small number of catchments. For the Arctic climatic zone, the number of observations was judged too low to draw reliable conclusions.

To explore further the differences in scale-dependence of SY-values for different climatic zones, a comparison was made between our SY-data and a data set of soil erosion rates, measured on runoff plots (≤0.0001 km^2) (Maetens *et al.*, 2009). To avoid bias, only plots without soil and water conservation measures were considered. Figure 4 displays the cumulative distributions of these soil erosion rates and our SY-data. In Fig. 4 a distinction is made between catchments and runoff plots in the Mediterranean climatic region and non-Mediterranean catchments and runoff plots. The non-Mediterranean data only contains SY and erosion rate data from the Boreal, Atlantic and Continental climatic zones as insufficient plot data were available for the other zones (i.e. Arctic, Steppic, Anatolian and Alpine). The results presented in Fig. 4 should be interpreted with care, as these cumulative distributions are based on data, collected under widely varying conditions. Nevertheless, some clear differences are visible. Plot erosion rates are generally higher than catchment SYs in the non-Mediterranean region, but lower in the Mediterranean region. This difference is partly due to the generally lower plot soil erosion rates in the Mediterranean region, but also due to generally higher catchment SY-rates, compared to the non-Mediterranean region (see Table 2).

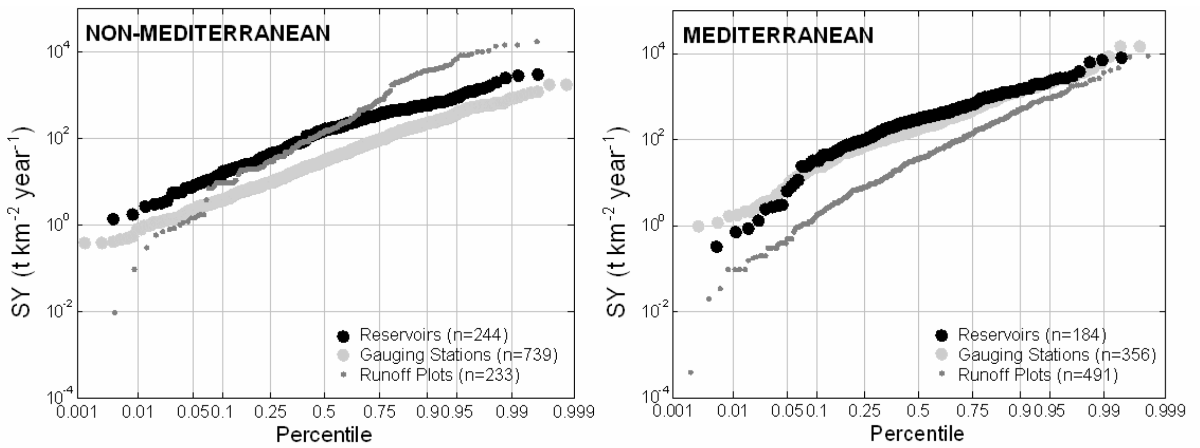

Fig. 4 Cumulative distributions of catchment SY-values and plot erosion rates. The non-Mediterranean data contains data from the Atlantic, Boreal and Continental climatic zone. "Reservoirs" indicate SY-values, derived from reservoir siltation rates; "Gauging Stations" indicate SY-values, measured at gauging stations; "Runoff Plots" indicate soil erosion rates, measured on runoff plots.

DISCUSSION

Considering the spatial variation of SY in Europe, our findings agree well with previous studies, reporting low SY-values in temperate and boreal climates and generally higher values in the Mediterranean world (Jansson, 1988; Woodward, 1995; Walling & Webb, 1996; Verstraeten *et al.*, 2006). Also, in a recent study from the USA, it was found that the highest sediment yields occur in hydrological units with a Mediterranean climate (Gonzales-Hidalgo *et al.*, 2009). It should be noted, however, that the observed differences are not only attributable to differences in climate. Important correlations exist between the climatic classification employed here and other physical factors relevant for SY. For example, the Alpine climatic regions in our analyses generally coincide with the mountain ranges of Europe. Milliman & Syvitski (1992) clearly indicated the important influence of relief on SY-fluxes. The observed higher SY-values for this climatic zone are therefore probably more a reflection of the high relief than of the climatic conditions in these areas. Many regions in the Mediterranean climatic zone are likewise characterized by steep topography and highly erodible lithologies, leading to higher sediment yields (Woodward, 1995). Also in the USA, the higher SY in the Mediterranean regions are not only attributed to differences in climate, but also to lithology and human influence (Gonzales-Hidalgo *et al.*, 2009). Furthermore, the majority of R-entries in our SY-database are situated in the Mediterranean and Alpine zones, while it can be expected that differences in methodologies lead in general to higher SY-values for R-entries than for GS-entries (e.g. GS-entries do not include bedload, while R-entries reflect the total load; Vanmaercke *et al.*, 2010). This is partly reflected in Fig. 4, where the cumulative distribution of SY-values, derived from reservoir siltation rates, is generally slightly higher than those measured at gauging stations.

A negative relationship is generally expected between sediment yield and catchment area, due to a decrease in topsoil erosion rates on more gentle slopes and an increase in alluvial sediment deposition with an increase in catchment size. However, many examples exist where no relation or a different relationship was found (e.g. Walling, 1983; Church & Slaymaker, 1989; de Vente *et al.*, 2007). For the Boreal, Atlantic and Continental climatic zone, our data seem consistent with this expectation, because erosion rates from runoff plots are generally higher than SY-values from catchments (Fig. 4) and a weak decreasing trend was found between SY and A (Table 1). For the Mediterranean, Alpine and Anatolian climatic zones, however, the SY-A trends showed a weaker (or no) decrease and more scatter, while plot soil erosion rates are generally lower than SY-values at the catchment scale for the Mediterranean region. This suggests a different relationship between catchment area and sediment yield. Generally lower soil erosion rates at the plot scale in the Mediterranean region have already been reported in previous studies (e.g. Poesen & Hooke, 1997; Cerdan *et al.*, 2006). Poesen & Lavee (1994) show that the Mediterranean region is generally characterized by more stony soils, while Poesen *et al.* (1994) discuss the significant effect of stoniness on the reduction of sheet and rill erosion rates at the plot scale. However, as catchment area increases, other erosion processes such as gully erosion, bank erosion and mass movements may contribute significantly to SY (de Vente & Poesen, 2005). As catchment area increases, SY can therefore first increase, reach a maximum at the medium-sized catchment scale and then decrease due to an increase in (flood plain) storage. This was, for example, illustrated with data sets of Spain and Italy (de Vente & Poesen, 2005; de Vente *et al.*, 2007).

The importance of other erosion processes (such as gullying, bank erosion and mass movements) and their effects on the scale-dependence of SY has important consequences for modelling sediment fluxes at the catchment scale. For example, the WATEM-SEDEM model (Van Oost *et al.*, 2000; Van Rompaey *et al.*, 2001) makes a RUSLE-based estimation of the sheet and rill erosion rate for each pixel and then assesses how much of the eroded sediment is routed to a next pixel and how much is deposited. This model was found to predict average sediment yields reasonably well for catchments in Belgium and the Czech Republic, but was unable to predict the SY for catchments in Spain or Italy (Van Rompaey *et al.*, 2001, 2003). De Vente *et al.* (2008) compared different spatially distributed erosion and sediment yield models for Mediterranean catchments. They observed that the catchment SY was higher than the gross-erosion rate due to sheet and rill erosion, predicted by the PESERA model (Kirkby *et al.*, 2004), illustrating the importance of other erosion processes. A model (SPADS) that takes other sediment sources into account was found to perform better than models that only consider the erosion processes on the hillslope and its associated sediment delivery.

CONCLUSIONS

Although significant improvements in understanding the controlling factors of sediment yield at the catchment scale have been made over the last decades, our insight into the regional variation of sediment fluxes on the European continent remains limited. An important factor, hampering a better understanding of these fluxes, is the lack of a synthesis and integration of existing (local) studies of sediment yield. Based on an extensive literature review, a database was developed which aims at bridging this gap. Measured SY-data from gauging stations and reservoirs in Europe were collected from various sources. This paper presents an overview of this data set and the first results obtained from analysis of the SY-data.

Important differences in SY were found between different climatic regions of Europe, with the highest median SY-values occurring in the Mediterranean and Alpine regions, and the lowest values in the Boreal and Atlantic zones. Significant differences were also observed in the SY-A relationships for the different climatic zones. These differences cannot, however, be attributed solely to climatic characteristics. Other physical factors also play an important role. This is reflected in the low coefficients of determination associated with the SY-A relationships for individual climatic zones. The results should therefore be interpreted with care. Nevertheless, our data suggests differences in scale-dependence between the non-Mediterranean (i.e. Atlantic, Boreal and Continental) zones and the Mediterranean zone. Whereas in the non-Mediterranean zone plot soil erosion rates are generally higher than catchment SY and SY tends to decrease with A, this seems not to be the case in the Mediterranean zone. In the latter zone, other sediment sources (such as gullies, bank erosion and mass movements) are often more important than sheet and rill erosion. Models that do not take these erosion processes into account, therefore often fail to provide meaningful predictions of SY in Mediterranean catchments.

Acknowledgments The research described in this paper was conducted within the framework of the EC-DG RTD – 6th Framework Research Programme (sub-priority 1.1.6.3) – Research on Desertification – project DESIRE (037046): Desertification Mitigation and Remediation of land – a global approach for local solutions. M. Vanmaercke received grant-aided support from the Research Foundation – Flanders (FWO), Belgium. The authors also wish to thank all researchers and institutes who provided data, publications or additional information on the sediment yield measurements discussed in this study.

REFERENCES

Aalto, R., Dunne, T. & Guyot, J. L. (2006) Geomorphic controls on Andean denudation rates. *J. Geology* **114**, 85–99.

Boardman, J. & Poesen, J. (2006) *Soil Erosion in Europe*. John Wiley & Sons Ltd., Chichester, UK.

Cerdan, O., Poesen, J., Govers, G., Saby, N., Le Bissonnais, Y., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.& Roxo, M. J. (2006) Sheet and rill erosion. In: *Soil Erosion in Europe* (ed. by J Boardman & J. Poesen), 501–513. John Wiley & Sons Ltd., Chichester, UK.

Church, M. & Slaymaker, H. O. (1989) Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature* **337**, 452–454.

de Vente, J.& Poesen, J. (2005) Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models. *Earth-Sci. Rev.* **71**, 95–125.

de Vente, J., Poesen, J., Bazoffi, P., Van Rompaey, A.& Verstraeten, G. (2006) Predicting catchment sediment yield in Mediterranean environments: the importance of sediment sources and connectivity in Italian drainage basins. *Earth Surf. Processes* **31**, 1017–1034.

de Vente, J., Poesen, J., Arabkhedri, M. & Verstraeten, G. (2007) The sediment delivery problem revisited. *Prog. Phys. Geogr.* **31**, 155–178.

de Vente, J., Poesen, J., Verstraeten, G., Van Rompaey, A. & Govers, G. (2008) Spatially distributed modelling of soil erosion and sediment yield at regional scales in Spain. *Global Planetary Change* **60**, 393–415.

Gonzales-Hidalgo, J. C., Batalla, R. J., Cerdá, A. & De Luis, M. (2009) Contribution of the largest events to suspended sediment transport across the USA. *Land Degrad Dev*. DOI: 10.1002/ldr.

Jansson, M. B. (1988) A global survey of sediment yield. *Geogr Ann A* **70**, 81–98.

Jetten, V. & Favis-Mortlock, D. (2006) Modelling soil erosion in Europe. In: *Soil Erosion in Europe* (ed. by J Boardman & J. Poesen), 695–716. John Wiley & Sons Ltd., Chichester, UK.

Kirkby, M. J., Jones, R. J. A., Irvine, B., Gobin, A, Govers, G., Cerdan, O., Van Rompaey, A. J. J., Le Bissonnais, Y., Daroussin, J., King, D., Montanarella, L., Grimm, M., Vieillefont, V., Puigdefabregas, J., Boer, M., Kosmas, C., Yassoglou, N., Tsara, M., Mantel, S., Van Lynden, G. J. & Huting, J. (2004) Pan-European soil erosion risk assessment: The PESERA Map, Version 1 October 2003. Explanation of Special Publication Ispra 2004 no.73 (S.P.I.04.73). *European Soil Bureau Research Report no. 16*, EUR 21176, 18 and 1 map in ISO B1 format. Office for Official Publications of the European Communities, Luxembourg.

Kovalchuk, I. P. & Vishnevskiy, V. I. (2004) Investigation of sediment yield of lowland rivers in Ukraine. In: *Sediment Transfer through the Fluvial System* (ed. by V. Golosov, V. Belyaev & D. E. Walling), 130–137. IAHS Publ. 288, IAHS Press, Wallingford, UK.

Maetens, W., Vanmaercke, M. & Poesen, J. (2009). Assessment of the effectiveness of soil and water conservation measures in reducing runoff and soil loss: establishment of a European database. In: *Advances in Studies on Desertification. Contributions to the International conference on Desertification in Memory of Professor John B. Thornes, Murcia 2009* (ed. by A. Romero Diaz, F. Belmonte Serrato, F. Alonso Sarria & F. López Bermúdez), 303–306. ICOD.

Merritt, W. S., Letcher, R. A. & Jakeman, A. J. (2003) A review of erosion and sediment transport models. *Environ. Modell. Softw.* **18**, 761–799.

Metzger, M. J., Bunce, R. G. H, Jongman, R. H. G, Mücher, C. A. & Watkins, J. W. (2005) A climatic stratification of the environment of Europe. *Global Ecol. Biogeogr.* **14**, 549–563.

Meybeck, M. & Ragu, A. (1995) River discharges to the oceans: an assessment of suspended sediment solids, major ions and nutrients. UN Environmental Programme (UNEP) report, Nairobi, Kenya.

Milliman, J. D.& Syvitski, J. P. M. (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geology* **100**, 525–544.

Milliman, J. D., Rutkowski, C. M. & Meybeck, M. (1995) River discharge to the sea. A global river index (GLORI). *LOICZ Reports & Studies, no. 2*. The Netherlands.

Mücher, C. A., Wascher, D. M., Klijn, J. A., Koomen, A. J. M.& Jongman, R. H. G. (2006) A new European Landscape Map as an integrative framework for landscape character assessment. In: *Landscape Ecology in the Mediterranean: inside and outside approaches* (ed. by R. G. H. Bunceand & R. H. G. Jongman) (Proc. European IALE Conference 29 March–2 April 2005, Faro, Portugal), 233–243. IALE Publication Series 3.

Poesen, J.& Hooke, J. M. (1997) Erosion, flooding and channel management in Mediterranean Environments of southern Europe. *Prog. Phys. Geogr.* **21**(2), 157–199.

Poesen, J. & Lavee, H. (1994) Rock fragments in top soils: significance and processes. *Catena* **23**, 1–28.

Poesen, J., Torri, D. & Bunte, K. (1994) Effects of rock fragments on soil erosion by water at different spatial scales: a review. *Catena* **23**, 141–166.

Rekolainen, S., Ekholm, P., Heathwaite, L., Lehtoranta, J.& Uusitalo, R. (2006) Off-site impacts of erosion: Eutrophication as an example. In: *Soil Erosion in Europe* (ed. by J Boardman & J. Poesen), 775–789, John Wiley & Sons Ltd., Chichester, UK.

Syvitski, J. P. M. & Milliman, J. D. (2007) Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *J. Geol.* **115**, 1–19.

Vanmaercke, M., Poesen, J., Verstraeten, G., de Vente, J., Maetens, W. & Ocakoglu, F. (2010) Sediment yield in Europe: spatial patterns, scale dependency and comparison with soil erosion rates. *Earth-Sci Rev* (submitted).

Van Oost, K., Govers, G. & Desmet, P. (2000) Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. *Landscape Ecol.* **15**, 577–589.

Van Rompaey, A., Verstraeten, G., Van Oost, K., Govers, G. & Poesen, J. (2001) Modelling mean annual sediment yield using a distributed approach. *Earth Surf. Proc. Landf.* **27**(11), 1221–1236.

Van Rompaey, A. J. J., Vieillefont, V., Jones, R. J. A., Montanarella, L., Verstraeten, G, Bazzoffi, P., Dostal, T, Krasa, J, de Vente, J. & Poesen, J. (2003) Validation of soil erosion estimates at European scale. *European Soil Bureau Research Report no. 13*, EUR 20827 EN, (2003), 26 Office for Official Publications of the European Communities, Luxembourg.

Verstraeten, G. (2006) Regional scale modelling of hillslope sediment delivery with SRTM elevation data. *Geomorphology* **81**(1–2), 128–140.

Verstraeten, G. & Poesen, J. (2000) Estimating trap efficiency of small reservoirs and ponds: methods and implications for the assessment of sediment yield. *Prog. Phys. Geogr.* **24**, 219–251.

Verstraeten, G., Bazzoffi, P., Lajczak, A., Radoane, M., Rey, F., Poesen, J. & de Vente, J. (2006) Reservoir and pond sedimentation in Europe. In: *Soil Erosion in Europe* (ed. by J Boardman & J. Poesen), 759–774. John Wiley & Sons Ltd., Chichester, UK.

Walling, D. (1983) The sediment delivery problem. *J. Hydrol.* **65**, 209–237.

Walling, D. E.& Webb, B. W. (1996) Erosion and sediment yield: a global overview. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. E. Walling & B. W. Webb) (Proceedings of the Exeter Symposium, July 1996), 3–19. IAHS Publ. 236. IAHS Press, Wallingford, UK.

Woodward, J. C. (1995) Patterns of erosion and suspended sediment yield in Mediterranean river basins. In: *Sediment and Water Quality in River Catchments* (ed. by I. Foster, A. Gurnell & B. Webb), 365–389. John Wiley & Sons Ltd., Chichester, UK.