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Sediment yield in Europe: spatial patterns and scale dependency

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Abstract

Our understanding about the regional variation of Sediment Yield (*SY*) in Europe and its scale dependency currently relies on a limited number of data for mainly larger river systems. *SY* is the integrated result of all erosion and sediment transporting processes operating in a catchment and is therefore of high value for environmental studies and monitoring purposes. Most global assessments of *SY* consider catchment area (*A*), climate and topography as the main explanatory variables. However, it is still unclear if these factors also control regional variations of *SY* within Europe. This paper aims at bridging this gap. Therefore, we i) present a large database of *SY*-values which was constructed through an extensive literature review; ii) describe the spatial patterns of *SY* across Europe; and iii) expore its relation with *A*, climate, and topography.

In total, sediment yield data from 1 794 different locations throughout Europe were collected (507 reservoirs and 1 287 gauging stations), representing a minimum of 29 203 catchment-year data. Only *SY*-data measured at gauging stations or derived from reservoir siltation rates over a period of minimum one year were included in the database. This database comprises a large range of catchment areas (*A*): i.e from small upland catchments ($\geq 0.01 \text{ km}^2$) to major European river basins ($\leq 1\,360\,000 \text{ km}^2$). An overview of the collected *SY*-data is provided and sources of uncertainty on the available data are discussed.

Despite potentially large uncertainties on several of the individual *SY*-values, analysis of this database indicates clear spatial patterns of *SY* in Europe. The temperate and relatively flat regions of Western, Northern and Central Europe generally have relatively low *SY*-values (with ca. 50% of the *SY* $< 40 \text{ t km}^{-2} \text{ y}^{-1}$ and ca. 80% of the data $< 200 \text{ t km}^{-2} \text{ y}^{-1}$), while Mediterranean and Mountainous regions generally have higher *SY*-values (with around 85% of the *SY*-data $> 40 \text{ t km}^{-2} \text{ y}^{-1}$ and more than 50% of the data $> 200 \text{ t km}^{-2} \text{ y}^{-1}$). These differences are attributed to a combination of factors, such as differences in climate, topography, lithology and land use. Although larger differences in *SY* were found between the climatic regions than between topographic zones, it is currently difficult to identify the individual importance of the various controlling factors of *SY*.

SY-*A* relationships were calculated for the entire dataset and for subgroups stratified according to measurement method (gauging stations or reservoir surveys), range of the catchment area, climatic region, topographic zone of the river outlet, and major European river system. Although typically a negative relationship between *SY* and *A* is expected due to a decrease in topsoil erosion rates on more gentle slopes and an increase in sediment deposition with an increase in catchment size, this relationship was found to be generally very weak and subject to a lot of scatter. Furthermore, results illustrate important differences in scale dependency: whereas a weak but significant negative trend is generally observed for the temperate and

relatively flat regions, no significant or even positive trends were observed in mountain regions and Mediterranean Europe. When only larger river catchments (i.e. $> 100 \text{ km}^2$ and especially $> 10\,000 \text{ km}^2$) are considered, catchment area exerted a larger control on *SY*. These findings confirm previous studies and indicate that the relationship between *SY*, spatial scale and other controlling factors is often complex and non-linear.

1. Introduction

Soil erosion by water has been intensively studied in Europe over the last decades (for an extensive overview see Boardman and Poesen, 2006) and is considered as one of the main threats to soil quality and productivity (EC, 2002; MEA, 2005). This research has led to a better understanding of the spatial patterns and intensity of water erosion processes at the hillslope scale in Europe (e.g. Kosmas et al., 1997; Kirkby et al., 2004; Poesen et al., 2006; Cerdan et al., 2010).

Area-specific sediment yield (*SY*, $\text{t km}^{-2} \text{ y}^{-1}$, i.e. the quantity of sediment reaching the catchment outlet per unit of time and per unit of area) at the catchment scale has also received considerable attention as it is crucial for many issues, such as capacity loss of reservoirs, damage to infrastructure, sedimentation of estuaries and harbours, coastal erosion, river delta development, eutrophication problems, the transportation of pollutants and damage to ecological habitats (e.g. Woodward, 1995; Owens et al., 2005; WCD, 2005; Rekolainen et al., 2006; Verstraeten et al., 2006). In addition, in drier environments *SY* can be an important desertification indicator (Vanmaercke et al., 2011).

Numerous papers have investigated the relationship between *SY* and various physical factors, such as climate, topography and catchment area, which are generally considered to be the dominant controlling variables at a global scale (e.g. Fournier, 1969; Jansen and Painter, 1974; Walling and Kleo, 1979; Milliman and Meade, 1983; Milliman and Syvitski, 1992;

Dedkov and Moszherin, 1992; Einsele and Hinderer, 1997; Syvitski and Milliman, 2007). Several studies indicated, however, that other factors such as lithology and land use may control *SY* at a local scale (e.g. Bruijnzeel, 2004; Nadal-Romero et al., 2011).

Especially the scale dependence of *SY* has received considerable attention. A negative relationship is generally expected between *SY* and catchment area (*A*, km²) due to a decrease in topsoil erosion rates on more gentle slopes and an increased probability of sediment deposition with an increase in catchment size (e.g. Dendy and Bolton, 1976; Walling, 1983). Catchment area is therefore often considered as the most important explaining factor of *SY*. Nevertheless, this relation can be strongly influenced by local factors, such as land cover, lithology, topography and human impacts, or the scale-dependent contribution of different erosion processes (de Vente and Poesen, 2005; de Vente et al., 2007). Moreover, the relationship between *SY* and *A* may change over time (Walling, 1983). Therefore, catchment area is in fact only a black-box parameter (e.g. Verstraeten and Poesen, 2001).

Over the last decades, *SY*-data have been collected for various regions and for catchments of various sizes. Several authors have made global inventories of available *SY*-data. Table 1 lists some of these datasets, reporting the total number of *SY*-observations as well as the number of observations for Europe. Although many of these datasets contain large numbers of *SY*-data, the data for European catchments are generally limited or correspond only to larger river systems (i.e. > 100 km²). An important problem is the lack of an overview of available *SY*-data for Europe. Whereas for the USA, an extensive standardized gauging network exists throughout the country, providing suspended sediment load data for more than 1400 catchments (monitored by the USGS, e.g. Gray and Gartner, 2010), as well as a detailed database on bathymetric surveys in more than 1800 reservoirs (e.g. Gray et al. 2010), *SY*-measurements in Europe are carried out by various institutions for different purposes. The results of these measurements are therefore scattered over various scientific papers, technical

reports and PhD theses, or remain unpublished. Furthermore, many *SY*-data have been published recently and are therefore not included in earlier established global compilations.

Current analyses of the regional patterns of *SY* at the European scale therefore do not fully exploit available *SY*-data and are mostly based on a limited number of observations, focussing mainly on the larger river systems (e.g. Walling and Webb, 1983; Milliman, 2001; Owens and Batalla, 2003; Delmas et al., 2009). A relatively large dataset with *SY*-data for 392 catchments in Europe was compiled by Verstraeten et al. (2006), but provides no complete overview of the available data as it only consists of *SY* estimates derived from reservoir siltation rates. Furthermore, the study of Verstraeten et al. (2006) was mainly descriptive and provides only a rough analysis of the spatial patterns and scale-dependency of *SY* in Europe. As a result, our understanding of the regional variation of *SY* and its relationship with spatial scale and other environmental variables within Europe is very limited.

This study aims to address this knowledge gap by compiling available *SY*-data in Europe and by providing a first exploration of the collected data at the continental scale, focussing on the potential importance of catchment area, topography and climate. The specific objectives are: i) to provide an overview of available *SY*-data in Europe; ii) to explore the spatial variability of *SY* in Europe; iii) to explore the scale dependency of *SY* in Europe; and iv) to discuss the accuracy of these results and to provide suggestions for further research.

2. Data collection and preparation

2.1. Construction of the sediment yield database

Based on an extensive literature review, sediment yield data of European rivers were collected from scientific publications, MSc. and PhD. theses and reports from hydrological institutes. The area considered in this study is indicated in Fig. 1. Only sediment yield data that were derived from measurements at a gauging station or from reservoir siltation rates, over a

measuring period of at least one year and for catchments with an area of at least 0.01 km² were considered. This catchment area threshold was arbitrarily chosen as smaller catchments can be expected to correspond almost entirely to hillslope systems with no central drainage system. Furthermore, very few studies reported measured *SY* for catchments smaller than 0.01 km².

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 measuring method (observation at a gauging station ('GS') or derived from a reservoir sedimentation rate ('R')), the location of the GS or R (i.e. the catchment outlet), the catchment area as reported in the original publication, the area-specific sediment yield, and the measuring period. For several entries, the measuring period was not reported but indicated to be longer than one year. In these cases, the measuring period was considered to be one year in our database. The coordinates of the catchment outlets were based on the originally reported coordinates. If original coordinates were unavailable, an assessment was made, based on the description of the catchment outlet in the publication, using Google™ Earth. If the catchment outlet could not be determined sufficiently accurate (e.g. when no location name was reported), the entry was not included in the database. Because many *SY*-data are reported in several sources, the database was checked for duplicate entries. Two entries were considered as duplicates if they had the same catchment outlet and (therefore) the same *A*. In such case, only the most reliable entry was included. This was generally considered to be the entry with the longest measuring period. If the measuring periods were equal or unknown, the source that provided the most detailed information on the catchment outlet and measuring technique was included.

The GS-entries in the database comprise *SY*-data, measured and calculated with a wide variety of techniques and procedures. For GS-entries, only the suspended sediment yield was

considered, as bedload data were unavailable for most gauging stations and dissolved load is beyond the scope of this study.

For R-entries, SY was estimated as (Verstraeten and Poesen, 2002):

$$SY = 100 \frac{SV \times dBD}{TE \times A} \quad (\text{Eq. 1})$$

With SV ($\text{m}^3 \text{ y}^{-1}$) being the annual sedimentation rate in the reservoir, dBD (t m^{-3}) the dry sediment bulk density and TE (%) the sediment trap efficiency of the reservoir. In many cases, not all variables of Eq. 1 were known. Some sources did only report SV but not dBD . For these entries a bulk density of 1.12 t m^{-3} was assumed, i.e. the average dBD of a large dataset of reservoir siltation rates (Verstraeten et al., 2006). Also TE was unknown in most cases (only for 9 reservoirs an accurate estimate was available). Generally, the TE of a larger reservoir is best predicted using the equation of Brune (1953), which relates TE to a ratio of the reservoir storage capacity and the annual inflow (Verstraeten and Poesen, 2002). However, for the majority of the reservoirs, no information on annual inflow was available. Hence, missing TE -values were estimated using an empirical equation proposed by Brown (1943) in Verstraeten and Poesen (2000):

$$TE = 100 \left(1 - \frac{1}{1 + 0.0021 D \frac{C}{A}} \right) \quad (\text{Eq. 2})$$

Where C is the reservoir storage capacity expressed (m^3) and D ($\text{km}^2 \text{ m}^{-3}$) a coefficient which depends on the operational characteristics of the reservoir. Values of D range between 0.046 and 1, with an average value of $0.1 \text{ km}^2 \text{ m}^{-3}$ (Verstraeten and Poesen, 2000). As the actual values of D were unknown, the average value was used to estimate all missing trap efficiencies.

2.2. Classification of the data

To analyse the collected data, entries were classified according to climate, topography and river basin. To classify the data according to climate, the LANMAP2 climatic classification was used (Mücher et al., 2006; Metzger et al., 2005). This classification is based on a principal component analysis of twenty relevant variables (e.g. monthly air temperature, monthly precipitation, hours of sunshine, altitude ...) and showed good agreement with other European classifications. Fig. 1 shows the climatic regions of Europe according to this classification. Using this subdivision, we classified all *SY*-data into eight climatic groups, based on the location of the catchment outlets. As some catchments are located in more than one climatic region, their assignment to the climatic region of the outlet may be disputable. However, this holds mainly for larger catchments. It was estimated that maximum 30% of the catchments cover more than one climatic region. For catchments smaller than 1 000 km² this is less than 5%, while 80% of the catchments larger than 10 000 km² are potentially situated in more than one climatic region.

Similar to the climatic classification, each entry was also assigned to a topographic class, based on the location of the catchment outlet: Lowlands (0-100 m a.s.l.), Hills (100-500 m a.s.l.), Low Mountain Ranges (500-1500 m a.s.l.), High Mountain Ranges (1500-2500 m a.s.l.) and Alpine Mountain Ranges (2500-5000 m a.s.l.). These five classes also correspond to the topographic subdivision of Europe according to the LANMAP2 classification (Mücher et al., 2006).

SY-data were also grouped according to the major river basin in which they are located. This was done by combining the locations of the catchment outlets with a map of the major European river catchments (Bredahl and Sousal, 2006).

3. Description of the database

The *SY*-database, consists of 1 794 entries (507 R- and 1 287 GS-entries). Table 2 gives an overview per country, while Fig. 1 displays the spatial coverage of the collected data. This map illustrates that some areas are densely covered with clusters of *SY*-data (e.g. Romania, Italy, Spain, and Turkey), while for other regions no or very few data were found (e.g. central France, Ireland, Belarus and Lithuania). For some regions, more *SY*-data exist, but were not available for this study (e.g. for Ukraine: Kovalchuk and Vishnevskiy, 2004). The overview presented here is therefore not complete but most likely covers the majority of available *SY*-data in Europe.

The sum of all measuring periods comprises a minimum of 29 203 catchment-year data. Fig. 2 indicates the cumulative distribution of the GS- and R-entries according to their measuring period. The average measuring period for GS-entries is 12 years (13.2 years when entries with unknown measuring period are excluded) and 27.1 years for R-entries (32.5 years without entries with an unknown measuring period). Fig. 3 displays the temporal coverage of the data, indicating the approximate number of entries that include a certain year in their measuring period. Only the entries for which both the start and end date of the measuring period were known could be included ($n = 1490$). This figure indicates that most GS-data were collected between 1950 and 2000, except for the Mediterranean region, for which many data were collected between 1930 and 1950. Many R-entries date back longer. 36 R-entries date back before 1900, while 138 R-entries date back before 1950. Most of the oldest reservoirs are situated in England.

Fig. 4 shows the frequency distribution of the entries and catchment-years according to their catchment area. Subdivisions are made according to measuring method and climatic region. These histograms indicate that most catchments have $100 < A < 10\,000 \text{ km}^2$. 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 corresponds more or less to the distribution of

the number of entries, except for entries with $1 < A < 10 \text{ km}^2$. This group has a relatively larger number of catchment years as it includes several old reservoirs in England for which long-term *SY*-values could be calculated. The Continental climatic region has the largest number of entries ($n = 608$), followed by the Mediterranean region ($n = 540$). The Atlantic ($n = 282$), Alpine ($n = 157$), Boreal ($n = 93$) and Anatolian ($n = 70$) regions are also relatively well presented, while the Steppic ($n = 37$) and especially the Arctic ($n = 7$) regions are poorly represented.

4. Analysis of the sediment yield database

4.1. Spatial patterns of sediment yield in Europe

Table 3 gives descriptive statistics of the collected data. When all data are considered the median and mean *SY* of R-entries are larger than those for GS-entries. Non-parametric Kruskal-Wallis tests indicate that the distribution of *SY*-values for R-entries differs significantly ($\alpha=0.05$) from the *SY*-distribution based on GS-entries. The differences in medians and means are, however, relatively small compared to the large range of *SY* observations and are not necessarily attributed to differences in measuring method.

Fig. 5 displays a map of all *SY*-values, grouped into three classes ($< 40 \text{ t km}^{-2} \text{ y}^{-1}$, $40 - 200 \text{ t km}^{-2} \text{ y}^{-1}$ and $> 200 \text{ t km}^{-2} \text{ y}^{-1}$). The boundaries of these classes were determined so that each class contained roughly 33% of the total number of entries. As the entries in the database comprise a large range of measuring procedures, measuring periods, catchment areas and catchment characteristics, differences in *SY* can not always be explained unambiguously. However, the use of only three arbitrary classes and the large number of observations make it possible to reveal some general patterns of *SY* in Europe. This map indicates that large parts of central, Western and Northern Europe are generally characterized by low *SY*-values ($< 40 \text{ t km}^{-2} \text{ y}^{-1}$). In Southern Europe *SY*-values above $40 \text{ t km}^{-2} \text{ y}^{-1}$ and even above $200 \text{ t km}^{-2} \text{ y}^{-1}$ are

much more frequent. Furthermore, several mountain ranges in Europe, such as the Alps, Apennines and Carpathians, can be clearly distinguished since most *SY*-values there are above 40 and even 200 t km⁻² y⁻¹.

Fig. 6 displays the cumulative frequency distribution of *SY* per climatic region. Table 3 reports descriptive statistics of the *SY*-values per climatic region. This comparison indicates some clear differences: the Mediterranean and Alpine regions generally have the highest *SY*-values, while the Atlantic and Boreal regions generally have the lowest *SY*. The Anatolian and Continental regions have intermediate values. For the Steppic and Arctic regions, the number of observations is too low to draw any conclusions. When the *SY*-data are grouped according to topographic zone (Fig. 6, Table 3), results indicate that the *SY*-distribution for catchments in lowlands plots generally below the *SY*-distributions for catchments in hills and mountain ranges. Hilly catchments also have generally lower *SY*-values than mountain ranges, but no clear differences between low, high and alpine mountain ranges can be observed. In general, *SY*-distributions differ less between topographic zones than between climatic regions.

4.2. Scale dependency of sediment yield and its regional variation

A graph of the *SY* versus the *A* of all entries reveals that the scatter is generally very large, with *SY* often ranging over 5 to 6 orders of magnitude for a given *A* (Fig. 7). It can be noticed that the variation in *SY* is generally lower for larger catchment areas: while the minimum values remain more or less constant, maximum values generally decrease with increasing *A*.

To further analyze the scale-dependency of *SY* in Europe, *SY*-*A* relationships were calculated.

These regressions were of the type:

$$SY = a \times A^b \quad (\text{Eq. 3})$$

with *a* and *b* empirical constants. Regressions were calculated in two ways: as ‘normal’ regressions, where all *SY* observations were considered equally important. This procedure

corresponds to the method used in other studies (e.g. de Vente et al., 2007). *SY*-values can, however, vary significantly from year to year. As a result, *SY*-values that are based on longer measuring periods can be expected to better represent the long-term average. Therefore, also ‘weighted’ regressions were calculated by attributing a weight to each observation, corresponding to the square root of the length of the measuring period (expressed in years). This was done in accordance to the central limit theorem which implies that the variation on a set of random observations is inversely proportional to the square root of the number of observations (Tijms, 2004). Table 4 reports all regression results, based on both the weighted and the normal method. However, as these weighted regressions are expected to be more reliable, all trend lines in the figures are based on the weighted regression results.

When all data are considered (Fig. 7, Table 4), a very weak but significant ($\alpha=0.05$) negative correlation is found. A slightly stronger, but still very weak negative correlation is found when only the GS-data are considered. For all R-data, no significant relationship was observed. Further, *SY*-*A* relationships were calculated for all *SY*-data with an $A < 100 \text{ km}^2$, $100 < A < 10\,000 \text{ km}^2$, and $A > 10\,000 \text{ km}^2$ (Table 4, Fig. 7). For catchments with $A < 100 \text{ km}^2$ no significant relationship was found, while for catchments with $100 < A < 10\,000 \text{ km}^2$ and catchments with $A > 10\,000 \text{ km}^2$, significant relationships were observed. The b-exponent of Eq. 3 becomes increasingly negative as the catchment area of the considered subset increases, pointing at a stronger decrease of *SY* with increasing *A*. Nevertheless, the associated r^2 -values are also very low (Table 4).

Fig. 8 displays the *SY*-*A* trends for all European river catchments for which more than 20 *SY*-observations were available. Most rivers in northern, eastern and western Europe, except the Ouse (Yorkshire, United Kingdom), have a significantly decreasing trend (Table 4). However, for rivers in Southern Europe (i.e. the Ebro, Po and Segura) an insignificant, positive relationship was found. Similar results were obtained with the ‘normal’ regression method.

The results of the *SY-A* regressions according to the climatic region of the catchment outlets, are given in Fig. 9 and Table 4. These results correspond relatively well to the observed cumulative *SY*-distributions (Fig. 6): the relationships of the Boreal and Atlantic regions plot the lowest, while those of the Mediterranean and Alpine regions generally plot the highest. A significant negative relationship was found for the Atlantic, Boreal and Continental regions for both the weighted and normal regression method (Table 4). However, the corresponding r^2 -values are very low. Also for the Steppic region, a significant negative relationship was found, but this regression is based on a rather limited number of observations and only includes catchments with a relatively large *A*. With the weighted regression method the Mediterranean and Alpine regions do not show a significant relationship. For the normal regression, however, the relationship for the Mediterranean region is weakly significant and negative. This is mainly due to some very small (i.e. $< 0.1 \text{ km}^2$) catchments situated in badlands with high *SY*-values but short measuring periods ($1600 - 8000 \text{ t km}^{-2}\text{y}^{-1}$, Descroix, 1994; Olivry and Hoorelbeck, 1989). The Arctic and Anatolian regions seem to have a positive *SY-A* trend, but the relationship for the Arctic region is not significant as it is based on very few observations. Also for the Anatolian region the trend is only barely significant ($p=0.049$) when the weighted regression method is applied and insignificant for the normal method.

Fig. 10 displays the regressions per climatic region, further subdivided according to the measuring method (GS or R). Regression details are given in Table 4. Although the number of observations and the range of catchment areas are sometimes too small to draw conclusions, these results clearly indicate that for a given *A*, R-entries have generally higher *SY*-values than GS-entries. Nevertheless, the observed pattern of Fig. 9 remains more or less consistent for both GS- and R-data. Only for the R-entries in the Atlantic region an

insignificant trend was observed, while for GS-entries in the Mediterranean regions a significant negative trend was found.

Fig. 11 displays the *SY-A* relationships for all catchments, grouped according to the topographic zone of the catchment outlets. Lowlands and hills reveal a significant negative relationship, although the associated r^2 -values were very low (Table 4). For low, high and alpine mountain ranges, no significant relationship was found. The slopes of these relationships (b-values in Table 4) further suggest that *SY* tends to decrease more with increasing *A* in lowlands than in the hills or mountainous ranges.

5. Discussion

5.1. Availability of sediment yield data

Fig. 1 indicates important differences in *SY*-data availability within Europe. Whereas some regions are densely covered with gauging stations and/or reservoirs, other regions in Europe are poorly represented. Although more *SY*-data probably exist for several of these regions, this literature review indicates that for some areas there are currently very few *SY*-data available (e.g. the Arctic regions and Ireland). Furthermore, the *SY* database reveals relatively few data for small catchments, (i.e. $< 100 \text{ km}^2$) and especially for catchments smaller than 1 km^2 (Fig. 4). While many of the *SY*-data for medium-sized and larger catchments (i.e. $> 100 \text{ km}^2$) were collected by national agencies, most *SY*-data for smaller catchments were collected for specific research purposes and are mainly published in scientific publications.

Regarding the temporal distribution, Fig. 3 clearly indicates that most data were collected between 1960 and 1990, with a peak around the 1980s. After this peak, the number of R- and especially GS-observations strongly declines. This sharp decrease is most likely related to the deterioration of many nation-wide gauging networks in the '90s and corresponds to a globally observed decrease of runoff gauging stations since the '80s (e.g. Vörösmarty, 2002).

5.2. Measuring method and quality of sediment yield data

The data considered in this study cover a wide range of measuring techniques and periods. As a result, the *SY*-data are of variable quality and have different degrees of uncertainties, depending on various factors. The total uncertainty on *SY*-values for *R*-entries is determined by the uncertainties on each of the factors in Eq. 1. (i.e. the uncertainty on *SV*, *dbd*, *TE* and *A*). The uncertainty on the annual sedimentation volumes were impossible to assess, as these mainly depend on the survey and interpolation method of the bathymetric surveys (Verstraeten and Poesen, 2002) and information on these methods or their accuracies was never reported.

Uncertainties on the dry bulk densities are probably small for the *R*-entries with measured *dbd*-values. A study of 13 ponds in Belgium, indicated that *dbd* varies relatively little within a reservoir, with coefficients of variation generally in the order of 10% (Verstraeten and Poesen, 2002). For 166 out of the 506 *R*-entries, however, *dbd* was not known and a value of 1.12 t m^{-3} was assumed, i.e. the average *dbd* of a global dataset of reservoir siltation rates (Verstraeten et al., 2006). For these *R*-entries, the induced uncertainty is of course larger. All measured *dbd*-values in this global dataset ranged between 0.14 and 1.7 t m^{-3} ($n = 528$). If we consider this range as representative for the range of *dbd*-values that can occur in a reservoir, this means that applying a *dbd* of 1.12 can overpredict the actual *SY* with a factor 8 or underpredict the *SY* with a factor 0.66. However, for most *R*-entries, induced uncertainty will, be smaller: 95% of the *dbd*-values in this global datasets range between 0.35 and 1.5 t m^{-3} and 68% between 0.87 and 1.4 t m^{-3} .

The estimated *TE*-values also induce uncertainty on the *SY*-values of *R*-entries. A detailed overview of various procedures to estimate *TE* indicated that Eq. 2 performs satisfying to estimate the long-term *TE* of larger reservoirs (Verstraeten and Poesen, 2000). Although *TE*-

values estimated with this equation may deviate from the actual long-term *TE*, e.g. because the value of *D* was unknown, applying these estimates is justified: not applying a correction for *TE* would systematically lead to an underestimation of *SY* for R-entries. However, the uncertainty associated with the unknown trap efficiencies is expected to be relatively small: less than 20% of the R-entries have an estimated *TE* of 50% or less, while more than half of the reservoirs have estimated *TE*s of 90% or more. Also the arbitrary *D*-value of 0.1 in Eq. 2 has little effect on most estimated *TE*s. For an R-entry with a C/A-ratio of $8 \times 10^4 \text{ hm}^3 \text{ km}^{-2}$ (the median C/A-ratio), the estimated *TE* is 95%. This value would change to 89% if the minimum *D*-value is used and to 99% if the maximum *D*-value is used.

The uncertainty for GS-observations also depends on various factors, which have been discussed in various studies. For example, Steegen and Govers (2001) report errors on *SY* in the range of 20% if suspended sediment concentration (*SSC*) is measured at a fixed point in the cross-section. These errors are explained by a concentration gradient in the flow cross-section and depend on flow characteristics as well as on the grain-size distribution of the sediments, but can be avoided by taking *SSC*-samples in a depth-integrated way (Steegen and Govers, 2001).

Teixeira and Caliri (2005) report errors of 20-30% on *SSC*-estimates, derived from turbidity measurements. Also the timing and frequency of sampling has a significant impact on the reliability of the *SY*-estimate. Uncertainty generally increases if the sampling frequency decreases, but depends on the used load estimate procedure and catchment characteristics (e.g. Webb et al., 1997; Phillips et al., 1999; Moatar et al., 2006). The magnitude of these errors is therefore difficult to assess, but can be larger than 100% when sampling was carried out very infrequently (e.g. once per month).

Various studies indicate that inadequate sampling schemes and sediment load estimate procedures not only lead to larger uncertainties, but also to a probability of underestimating

the actual *SY* at gauging stations. Steegen et al. (2000) found that time-spaced sampling underestimated the *SY* of a 250 ha catchment in central Belgium by 20-35% compared to flow-proportional sampling ('storm chasing'). Ferguson (1986) illustrated that sediment loads, derived from logarithmically transformed data, may underestimate the true sediment load with errors up to 50% due to statistical considerations. Correction factors or the use of non-linear regression techniques can avoid this bias (e.g. Asselman, 2000). However, these correction factors are not always applied. Also low sampling frequencies not only induce uncertainties but tend to underestimate the actual load. This was observed for load estimates based on rating curves (e.g. Webb et al., 1997), as well as on discharge-weighted mean sediment concentrations (e.g. Moatar et al., 2006). Furthermore, the GS-entries in this study only include suspended sediment loads, while *SY*-estimates derived from reservoir surveys also include bedload. A review by Turowski et al. (2010) illustrates that bedload may be a substantial fraction of the total load, especially for sand-bed rivers (30-50%) and smaller catchments. However, the importance of bedload for individual rivers can currently not be predicted accurately (Turowski et al., 2010).

The inter-annual variability of *SY* also induces uncertainties. The confidence in mean values that may be biased by the presence or absence of extreme events is a classical problem in fluvial geomorphology, especially for short-term time series (e.g. Kirkby, 1984; Gonzalez-Hidalgo et al., 2009). As GS-entries generally have shorter measuring periods than R-entries (Fig. 2), uncertainties due to inter-annual variation are expected to be larger for GS-entries.

Finally, catchment areas are also subjected to uncertainties and potentially induce errors on the *SY*-values. Accuracies of the reported *A*-values are rarely reported, but are expected to be relatively small (Verstraeten and Poesen, 2002).

This non-exhaustive overview indicates that all *SY*-values are subjected to several sources of uncertainties. However, for none of the *SY*-entries it was possible to assess the total

uncertainty, as this depends on various unknown site- and method-specific factors. Nevertheless, considering all the discussed sources of uncertainty suggests that total uncertainties may rise well over 100% for some *SY*-entries (e.g. for GS-observations with a very short measuring period and low SSC sampling frequency).

5.3 Reliability of the obtained spatial patterns and scale-dependency results

Given the potential errors associated with the reported *SY*-data, the results discussed in section 4 need to be interpreted with caution. Inaccurate *SY*-data could partly explain why most *SY*-*A* relationships have such a poor correlation (Table 4). However, it can be expected that *SY*-estimates will not differ more than one or two orders of magnitude from their actual values, while *SY* can vary up to six orders of magnitude for a given *A* (Fig. 7). The observed variability is therefore clearly not only a result of measuring uncertainties, but also from other controlling factors of *SY*. Moreover, the observed spatial patterns of *SY* are based on relatively large numbers of data, reducing the importance of possible measuring errors. For example, the discussed differences in cumulative frequency distribution between climatic regions are generally valid for 90% to 95% of the distributions, which often include more than 70 observations collected with various methods (Fig. 6). Furthermore, some entries in Fig. 5 may be attributed to a wrong *SY*-class, but this would have only a limited effect on the discussed pattern.

The inter-annual variability of *SY* could also have an effect on the obtained results, because many entries have relatively short measuring periods (Fig. 2). This variability was partly taken into account by calculating weighted *SY*-*A* relationships. Nevertheless, analysis of the residues of both normal and weighted regressions revealed no correlation between the absolute values of the residues and the corresponding measuring periods.

The very poor correlations between *SY* and *A* for most of regressions (Table 4) therefore mainly indicate that other factors than *A* exert a stronger control on *SY*. Various studies have indicated that factors such as climate (e.g. Jansen and Painter, 1974; Wilson 1977; Jansson, 1982; Syvitski and Milliman, 2007), topography and tectonics (e.g. Milliman and Syvitski, 1992; Montgomery and Brandon, 2002), lithology (e.g. Woodward, 1995; Nadal-Romero et al., 2011), the presence of glaciers (e.g. Hallet et al., 1996; Hinderer and Einsele, 2001), land use and human impacts (e.g. Walling, 2006; Vanacker et al., 2007) and the presence of lakes and reservoirs (e.g. Vörösmarty et al., 2003; Walling, 2006) may have a large influence on catchment *SY*. Many of these factors are not (explicitly) considered in the classifications used. For example, a visual comparison of Fig. 5 with maps indicating seismic activity in Europe (Cloetingh et al., 2005), revealed good correspondence: high *SY*-values generally occur in tectonically active regions, such as the Alps, the Pyrenees, the Apennines and Anatolia. Also (natural) lakes may have a significant influence on the observed patterns, since they trap large fractions of eroded sediments (e.g. Einsele and Hinderer, 1997). Around three quarters of the more than 500 000 natural lakes larger than 0.01 km² in Europe are located in the Boreal region (Stanners and Bourdeau, 1995), which may help explaining the low *SY*-values for this region (Fig. 6). Furthermore, results are based on data, collected over different periods of time (Fig. 3). Variation in *SY* can therefore also partly be attributed to temporal variations in weather conditions or landuse. For example, several countries of Eastern Europe have undergone significant land use changes during the last decades (e.g. Van Rompaey et al., 2003).

An important consideration is that correlations exist between several of these factors. As Table 5 illustrates, many considered climatic regions concur strongly with specific topographic zones, and measuring methods (GS or R). For example, for the Boreal region, most catchment outlets are located in hills and lowlands. Based on the classifications used, it

is impossible to assess if the generally low *SY*-values for this region (Fig. 6) are mainly a result of climatic or topographic factors, as lowlands and hills were also characterized by generally lower *SY*-values (Fig. 6). Similar considerations can be made for other regions: the Alpine, Anatolian and Mediterranean climatic regions are characterized by larger *SY*-values, but also by generally more entries located in mountainous areas (Table 5). It could be argued that a further subdivision of the data, i.e. according to both climatic region and topographic zones, would allow a better identification of the controlling factors. However, such approach was found unreliable since for most of these resulting groups, the number of *SY*-observations and the range of catchment areas would be very low, leading to even less reliable *SY*-*A* relationships (e.g. De Boer and Crosby, 1996).

Interpretation of the obtained spatial patterns and *SY*-*A* relationships is not only impeded by covariation between explanatory variables, but also by their correlation with the measuring methods. For example, most entries in the Boreal region were derived from GS-observations, while the Mediterranean and Alpine region have relatively more R-entries (Table 5). As discussed in the previous section, GS-entries have a relatively larger probability of underestimating the actual *SY*, which may contribute to the observed differences. This is also indicated in Fig. 10, where for almost every climatic region, the *SY*-*A* regression based on R-data plots above the regression line based on GS-data. However, also these differences can not merely be attributed to differences in measuring method because reservoirs are probably more likely to occur in areas with a higher relief potential or erosion risk, compared to gauging stations (e.g. Verstraeten and Poesen, 1999). Furthermore, it can be expected that bathymetric surveys are more frequently conducted in reservoirs with a high sedimentation rate, which could also bias the results towards higher *SY*-values for R-data. Also the difference in the *SY*-*A* relationship for GS- and R-entries in Fig. 7 is most likely explained by both differences in measuring method, as well as by geographical factors (Table 5). Based on

the available data, it is currently impossible to assess the precise impact of the different measuring methods on the obtained results. Nevertheless, observed differences between GS- and R-data in Fig. 10 are generally less than one order of magnitude.

5.4 Interpretation of the results and comparison with literature

The analysis presented here confirms earlier studies that *SY-A* relationships can certainly not be used straightforward for predictive purposes (e.g. Walling, 1983; de Vente and Poesen, 2005). Furthermore, differences in the cumulative frequency distributions (Fig. 6) or *SY-A* relationships between climatic or topographic regions (Fig. 9, 10 and 11) can not merely be attributed to differences in either climate or topography, due to their correlation with other factors.

Nevertheless, important lessons can be learned from the obtained results. The climatic regions shown in Fig. 1 provide a meaningful subdivision of Europe in physical regions with different characteristics (Mücher et al., 2006; Metzger et al., 2005). Important differences in *SY* were observed between those regions which reflect at least partly differences in environmental characteristics (Fig. 5, 6). Previous studies, based on smaller datasets, reported similar patterns and also related these to various interrelated factors, such as climate, topography, lithology and land use (Jansson, 1988; Woodward, 1995; Walling and Webb, 1996; Milliman, 2001; Verstraeten et al., 2006). The importance of these factors is reflected in the very low correlation coefficients of the calculated *SY-A* relationships for the entire dataset (Fig. 7).

SY-A relationships for catchments within the same region or with similar characteristics can yield stronger correlations, as this can reduce the effect of these other controlling factors. Several studies reported much stronger *SY-A* relationships when only data of a specific region are considered (for a review: see de Vente et al., 2007). Also in this study better *SY-A* relationships were found for some climatic regions (Fig. 9), topographic zones (Fig. 11) or

river basins (Fig 8). However, the explained variance of these regressions remains low, and regressions for several regions or catchments were insignificant. The obtained relationships therefore mainly illustrate that A explains only a small part of the observed variation in SY at a regional scale. Despite their low explaining power, the calculated SY - A relationships also indicate important regional differences in scale dependency for Europe. Whereas weak but significant negative trends were found for most catchments in northern, western and central Europe, this was generally not the case for catchments in southern Europe and mountain regions. This pattern remains more or less consistent when regressions were calculated according to climatic region (Fig. 9), river basins (Fig. 8) and topographic zone (Fig. 11), and for both the weighted and normal regressions (Table 4).

This finding is also in line with previous studies. de Vente and Poesen (2005) suggest that SY in Mediterranean environments can be expected to first increase with A , because of the increasing sediment contribution from different erosion processes. Whereas sheet and rill erosion processes are the major sediment producing processes at the plot scale ($A < 10^{-3} \text{ km}^2$), other erosion processes such as gullies, landslides and river bank erosion may contribute significantly to SY as A increases. Only when spatial scale further increases (i.e. $A > 10^2 \text{ km}^2$), the effect of sediment sinks override the importance of these sediment sources, resulting in a gradual decline of SY . The lack of a significant and continuously negative relationship for the Mediterranean (and Anatolian) region (Fig. 9) seems to confirm the conceptual model of de Vente and Poesen (2005). Further confirmation was found when a comparison between the collected SY -data and a data set of soil loss rates, measured on runoff plots ($A < 10^{-4} \text{ km}^2$) for a range of conventional land uses (Vanmaercke et al., 2011). Soil loss rates at the plot scale were found to be generally higher than catchment SY in Non-Mediterranean region, which corresponds to the common expectation that SY decreases with increasing A . For the Mediterranean region, however, SY -values were generally larger than soil losses at the plot

scale, illustrating the importance of other erosion processes than sheet and rill erosion in this region.

Also for mountain regions, the expected decrease in SY with increasing A is probably overridden by the importance of other sediment-producing processes, explaining why no significant trend was found for the Alpine regions (Fig. 9) and mountain ranges (Fig. 11). Landslides, for example, can be expected to occur more frequently in mountain regions, due to their steep slopes and often higher tectonic activity (e.g. Korup, 2005; Montgomery and Brandon, 2002; Cloethingh et al., 2007). Although few quantitative data are available, it is known that landslides may contribute significantly to SY (e.g. Korup et al., 2004; Bathurst et al., 2005). The presence of glaciers can also have a major impact on SY and its scale dependence in mountainous catchments (e.g. Hallet et al., 1996; Hinderer and Einsele, 2001). Furthermore, it can be expected that mountain ranges have relatively fewer areas where sediments can be redeposited and stored compared to lowlands and hilly regions, as the possibility to redeposit sediments is strongly controlled by the local gradient. For example, a quantification of postglacial storage in the Alps, indicated that 90% of the areas where sediment is stored occurs in the lowest 25% of the mountain belt (Straumann and Korup, 2005). Similarly, the location of the dominant sediment source areas within a catchment can also exert an influence on the observed SY - A trend (e.g. de Vente et al., 2007). Whereas for many rivers (e.g. the Rhône, originating in the Alps) the distance from the most important sediment source area to the outlet (and hence the probability of sediment redeposition) increases with increasing A , the Ebro and Po run more or less parallel to a mountain range (the Pyrenees and the Alps respectively). This may help explaining why for these two rivers, no significant negative SY - A relationship was found (Fig. 8, Table 4).

The importance of local factors on SY can be expected to be smaller for large river systems (e.g. $A > 10\,000\text{ km}^2$). Larger catchments generally consist of a patchwork of land uses and

geomorphic units. Local conditions are therefore less likely to override general trends, as they often average out at larger scales. Furthermore, mean slope gradient generally decreases with increasing A and the importance of sediment sinks can be expected to further increase (e.g. de Vente and Poesen, 2005). This is in line with our results. While no significant SY - A trend was found for all catchments smaller than 100 km², significantly negative trends were observed for catchments of 100 – 10 000 km² and for catchments > 10 000 km² (Fig. 7, Table 4). Although r^2 -values are still very low, the observed slopes of the regression equations are much steeper than most of the slopes for the other calculated SY - A relationships ($b = -0.28$ and -0.33 , respectively, Table 4). These values also agree more with the reported slope value of -0.5 that is often used for global prediction purposes and that was mainly based on observations for the largest river systems in the world (e.g. Syvitski et al., 2005; de Vente et al., 2007).

6. Conclusions and scope for further research

So far, studies assessing the regional variation of SY in Europe were based on a relatively limited number of SY -data, focussing mainly on larger river systems. An overview of pan European patterns of SY and its relationship with topography, climate and spatial scale was lacking. This study aimed to synthesize all available SY -measurements in Europe and to provide a first analysis of the collected data.

The data considered in this study were collected under widely varying conditions using different methods. Although the potential sources of error on SY -measurements are well known, the uncertainty on the individual SY -observations could not be assessed because this requires detailed information on the measuring and calculation method which is mostly unknown and rarely reported. Methods and criteria that allow a rough assessment of the involved uncertainty on SY -measurements based on generally available data would be of great

value, since these would allow to better assess the reliability of *SY*-measurements conducted in the past.

Despite potentially large uncertainties on several *SY*-observations, important regional differences in *SY* can be noted. Whereas most catchments in northern, western and central Europe are characterized by relatively low *SY*-values (ca. 50% of the *SY* < 40 t km⁻² y⁻¹ and ca. 80% of the data < 200 t km⁻² y⁻¹), Mediterranean and Mountainous regions generally have higher *SY*-values (around 85% of the *SY*-data > 40 t km⁻² y⁻¹ and more than 50% of the data > 200 t km⁻² y⁻¹). As these differences are based on large numbers of observation, they cannot only be attributed to uncertainties on the available data but must be the result of regional variation of the controlling factors of *SY* and potentially of different dominant erosion processes.

Based on the current analyses, the individual importance of the various potential controlling factors could not be determined. Subdividing the data according to topographic zone and especially according to climatic region revealed some differences, but the variability of *SY* within each region or zone remained very large. This indicates that other factors probably play a larger role at a regional scale. Moreover, important auto-correlations exist between factors that potentially explain the observed *SY*-differences, which also impede a clear interpretation. Furthermore, calculated *SY*-*A* relationships explained little of the observed variation, are region-specific and scale-dependent.

These findings confirm earlier studies indicating that the relationship between *SY*, spatial scale and other controlling factors is often complex and non-linear. Hence, *SY*-*A* relationships are an inadequate tool to predict *SY* at subcontinental scale, as they do not allow to identify the major controlling factor and as they are subjected to large uncertainties. While, sediment fluxes of large river systems at a global scale were found to be mainly controlled by climate, relief and catchment area (e.g. Syvitski et al., 2005; Syvitski and Milliman, 2007), the

importance of these factors could not clearly be identified in this study. Future research attempting to predict catchment *SY* at a regional scale should therefore aim to improve our understanding of the controlling factors and processes of *SY* and assess how these vary with spatial scale. Modelling studies and statistical analyses of *SY* already improved our understanding considerably. However, their results are either only valid for specific regions (e.g. Van Rompaey et al., 2001; de Vente et al., 2005; de Vente et al., 2006) or focus mainly on larger river systems (e.g. Delmas et al., 2009). Models aiming to predict *SY* for different regions and catchment scales face the difficulty of having to consider all relevant erosion and sediment deposition processes, while keeping input data requirements at a feasible level (e.g. Merriit et al., 2003; de Vente et al., 2008).

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TABLES AND FIGURES

Tables:

Table 1: Overview of global inventories of sediment yield data, their total number of entries (# Entries), the number of entries for Europe and their corresponding range of catchment areas (A).

Reference	Total # Entries	# Entries in Europe	Min. A (km ²) for Europe	Max. A (km ²) for Europe
Holeman, 1968	110	20	1 831	1 350 653
Fournier, 1969	139	93	14.8	193 900
Jansen and Painter, 1974	79	22	5 288	1 350 085
Walling and Kleo, 1979	1 246	396	N.A.	N.A.
Walling and Webb, 1983	< 1 500	N.A.	1 000 - 10 000 ¹	
GLORI: Meybeck and Ragu, 1995	219	45	2 000	817 000
LOICZ: Milliman et al., 1995	401	112	110	810 000
Jansson, 1988	1 358 ²	445	> 300 ³	N.A.
de Araujo and Knight, 2005	364	55	> 0.01 ⁴	< 10 000 ⁴
Dedkov and Gusarov, 2006	4 140	N.A.	N.A.	N.A.
FAO, 2008	869	123	100	1 800 000

N.A.: not available. ¹: Actual min and max A unknown. Authors only report that the presented global SY -map aims to represent the SY of basins of 1 000 - 10 000 km². ²: # Entries for Europe does not include soviet union. From the publication it was unclear which 188 entries of the soviet union are situated in Europe. ³: 300 km² is the minimum A for the global dataset. The min A for the European data could not be estimated. ⁴: min. and max. A estimated from figure in publication.

Table 2: Overview of the collected SY-data. For each country, the number of gauging stations (GS) and reservoir (R) entries, the corresponding number of catchment-years, and the sources of the data are indicated.

Country	# GS-entries (catch. yr)	# R-entries (catch. yr)	Total # entries (catch. yr)	Source
Albania	11 (169)	-	11 (169)	IAHS (1974); Grahzdani (2006)
Austria	22 (234)	23 (446)	45 (680)	Schröder and Theune (1984); Tschada and Hofer (1990); Habersack (1996); Batuca and Jordaan (2000); White (2001); Meybeck et al. (2003)
Azerbaijan	-	1 (19)	1 (19)	Golosov (pers. comm)
Belarus	-	1 (27)	1 (27)	Golosov (pers. comm)
Belgium	36 (94)	22 (142)	58 (236)	Witrix and Lorent (1966); Sine and Agneessens (1978); Bollinne (1982); Lamin et al. (1987); Huybrechts et al. (1989); Lamalle et al. (1989); Voet (1997); Huygens et al. (2000); Steegen (2001); Verstraeten and Poosen (2001); Vanlierde et al. (2005); Van Hoestenburgh et al. (2008); Petit (pers. comm)
Bosnia and Herzegovina	4 (4)	-	4 (4)	Jovanovic and Vukcovic (1957)
Bulgaria	46 (1354)	-	46 (1354)	Gergov (1996); Jaoshvili (2002)
Croatia	1 (1)	-	1 (1)	Jovanovic and Vukcovic (1957)
Cyprus	-	7 (22)	7 (22)	White (2001)
Czech Republic	36 (279)	10 (315)	46 (594)	Cyberzki (1973); Krása et al. (2005); Dostal et al. (2006); Becvar (2007); Kadlac et al. (2007)
Denmark	23 (59)	-	23 (59)	Hasbølt (1983); Hasbølt (1991); Lambel et al. (1999); Thodsen et al. (2004)
Estonia	1 (1)	-	1 (1)	RIKZ et al. (2004)
Finland	36 (478)	-	36 (478)	Niemi et al. (2001); Vuorenmaa et al. (2002); Räske et al. (2003); Lepistö et al. (2006); Tattari and Raskolainen (2006); Puntinen et al. (2007); Finnish Environment Institute (2008)
France	88 (360)	13 (113)	101 (473)	Survey and Deleglise (1967); Jansen and Painter (1974); Cadillon et al. (1981); Fauroux (1981); Vivian and Thomas (1982); Schröder and Theune (1984); Jauffret and Verague (1986); Cravero and Guichon (1989); Olivry and Hoerelbeck (1989); Desroix (1994); Martin et al. (1997); Sogon et al. (1999); Asselman (2000); Batuca and Jordaan (2000); Pont et al. (2002); Schäfer et al. (2002); Coynel et al. (2003); Esteves and Ludwig (2003); Meybeck et al. (2003); RIKZ et al. (2004); Mano et al. (2006); Moser et al. (2006); Lefrançois et al. (2007)
Georgia	23 (23)	-	23 (23)	Jaoshvili (2002)
Germany	129 (2065)	17 (168)	146 (2233)	Nippes (1971); Cyberzki (1973); IAHS (1974); Flögel (1982); Schröder and Theune (1984); Weiss (1996); Bauer and Tille (1967); Asselman (2000); Bayar, LfH (2002); Meybeck et al. (2003); RIKZ et al. (2004)
Great Britain	33 (89)	63 (4486)	96 (4575)	McMannus and Duck (1985); Labada et al. (1991); Milliman and Syvitski (1992); Butcher et al. (1993); Milliman et al. (1995); Foster and Lees (1999); Wass and Lees (1999); Barlow and Thompson (2000); Bromsdon and Naden (2000); Small et al. (2003); RIKZ et al. (2004); Evans and Warburton (2005); Harlow et al. (2006)
Greece	13 (97)	3 (45)	16 (142)	Milliman et al. (1995); Poulos et al. (2000); RIKZ et al. (2004); Zarris and Koutsoyiannis (2005); Zarris et al. (2007)
Hungary	25 (208)	7 (111)	32 (319)	Bogardi (1957); IAHS (1974); Bogardi et al. (1983); Sisak et al. (2007); Csafordi et al. (2008); Csafordi et al. (2009)
Iceland	5 (73)	-	5 (73)	Lawler (1994); Pálsson et al. (2000); Old et al. (2005); Beylich and Kneisel (2009)
(Northern) Ireland	12 (12)	-	12 (12)	RIKZ et al. (2004); Evans et al. (2006); Harrington and Harrington (2009)
Italy	130 (1589)	52 (1326)	182 (2915)	Frosini (1948); Gazzolo and Bassi (1960); IAHS (1974); De Casa and Giglio (1981); Schröder and Theune (1984); Tropeano (1984); Basoffi (1987); Tamburino (1989); Tamburino (1990); Milliman and Syvitski (1992); Milliman et al. (1995); White (2001); Ferro et al. (2003); Porto et al. (2004); RIKZ et al. (2004); Van Rompaey et al. (2005); Terri et al. (2006); Pavanelli and Rigotti (2007); Grasso et al. (2008)
Lithuania	3 (20)	-	3 (20)	IAHS (1974); Pastelnikovs (1994); RIKZ et al. (2004)
Luxembourg	5 (18)	-	5 (18)	Verstraeten (1977); Duijsings (1986); Cammeraat (2002); Martinez-Carreras et al. (2010)
Macedonia	3 (18)	2 (45)	5 (63)	Jovanovic and Vukcovic (1957); Skoklevski and Velickov (1995); Trendafilov (1996); Blinikov (1998)
Moldova	1 (1)	1 (28)	2 (29)	RIKZ et al. (2004); Golosov (pers. Comm)
Montenegro	1 (1)	-	1 (1)	Jovanovic and Vukcovic (1957)
Netherlands	8 (48)	-	8 (48)	IAHS (1974); Van Dijk and Kwad (1996); RIKZ et al. (2004)
Norway	49 (278)	-	49 (278)	Bogen (1995); Bogen (1996); Hodson et al. (1998); Bogen and Benness (2003); RIKZ et al. (2004); Bogen and Benness (2005); Øygarden et al. (2006)
Poland	63 (1794)	23 (504)	86 (2298)	Fröhlich (1975); Schröder and Theune (1984); Fröhlich (1986); Rojek and Zmuda (1992); Bednarczyk and Madeyski (1996); Branski and Banasik (1996); Lajczak (1996); Bednarczyk and Madeyski (1998); Zmuda (1998); White (2001); Lajczak (2003); RIKZ et al. (2004); Fröhlich and Walling (2005); Hejduk et al. (2006)
Portugal	10 (35)	5 (66)	15 (101)	DIAG (1997); Milliman et al. (1995); White (2001); RIKZ et al. (2004)
Romania	175 (1574)	49 (632)	224 (2206)	Diaconu (1969); RIKZ et al. (2004); Rădoane and Rădoane (2005)
Russia	16 (186)	15 (568)	31 (754)	IAHS (1974); Milliman and Syvitski (1992); Dimitrov et al. (2003); RIKZ et al. (2004); Golosov (pers. comm)
Serbia	7 (18)	6 (58)	13 (76)	Jovanovic and Vukcovic (1957); Kostadinov and Markovic (1996); Pedovic et al. (1999)
Slovakia	-	25 (25)	25 (25)	Jansky (1992); Haight et al. (2004)
Slovenia	3 (4)	-	3 (4)	Jovanovic and Vukcovic (1957)
Spain	17 (71)	111 (3774)	128 (3845)	Balasch et al. (1992); Avendaño Salas et al. (1995); Avendaño Salas and Cobo Rayán (1997); Avendaño Salas et al. (1997); Llovet et al. (1998); Alvera and Garcia-Ruiz (2000); Regués et al. (2003); RIKZ et al. (2004); Balasch et al. (2005); de Vente et al. (2005); Rovira et al. (2005); Rovira and Batalla (2006); Sando Fouz et al. (2006); Boix-Fayos et al. (2007); Nadal Romero et al. (2007); Boix-Fayos et al. (2008); Casali et al. (2008); Garcia-Ruiz et al. (2008); Soler et al. (2008)
Sweden	37 (554)	-	37 (554)	Milliman et al. (1995); Meybeck et al. (2003); Beylich and Gintz (2004); RIKZ et al. (2004); Beylich et al. (2006); SMHI (2008)
Switzerland	46 (649)	28 (691)	74 (1340)	Beyer Portner (1998); Blanc et al. (1989); FOWG (2008); Schröder and Theune (1984)
Turkey	162 (2952)	16 (16)	178 (2968)	Milliman et al. (1995); Göğüş and Yener (1997); White (2001); Dimitrov et al. (2003); ERI (2005)
Ukraine	7 (42)	7 (124)	14 (166)	IAHS (1974); Jansen and Painter (1974); Milliman et al. (1995); Dimitrov et al. (2003); Golosov (pers. comm)
Total	1287 (15452)	507 (13751)	1794 (29203)	

Table 3: Statistical description of the catchment area (A , km²) and sediment yield (SY , t km⁻² y⁻¹) for all entries per measuring method (gauging stations (GS) or reservoirs (R)), climatic region (see Fig. 1) and topographic zone.

	number of obs.	min	median	A (km ²)					SY (t km ⁻² y ⁻¹)		
				mean	max	Std.	min	median	mean	max	Std.
All SY data											
All data	1794	0.01	791	14 460	1 360 000	76 683	0.3	92	341	30 000	1 113
All GS data	1287	0.01	1 193	12 660	1 350 659	54 592	0.4	63	279	30 000	1 162
All R data	507	0.01	148	19 027	1 360 000	115 036	0.3	227	498	12 000	959
SY data: per Climatic Zone											
Alpine	157	0.30	203	764	10 550	1 480	0.9	198	451	8 990	876
Anatolian	70	43.50	3 417	6 343	36 642	8 352	1.4	144	366	4 299	683
Arctic	7	0.70	7	15	33	15	27.9	98	148	359	126
Atlantic	282	0.10	135	10 199	163 896	27 764	0.4	28	100	2 834	243
Boreal	93	0.10	2 054	17 356	229 000	36 281	0.5	6	40	1 256	141
Continental	608	0.04	1 147	19 668	1 280 000	92 648	0.5	70	177	4 678	338
Mediterranean	540	0.01	722	5 189	97 800	14 197	0.3	218	673	30 000	1 863
Steppic	37	48.00	9 700	165 574	1 360 000	330 504	1.8	60	281	1 980	419
SY data: per Topographic Zone											
Lowland (0-100 m)	413	0.01	2 096	40 518	1 360 000	138 111	0.5	35	232	8 990	657
Hills (100-500m)	842	0.04	762	9 588	1 210 000	52 168	0.4	84	271	4 678	495
Low Mountain Ranges (500-1500m)	434	0.01	582	2 302	50 068	5 246	0.3	174	568	30 000	2 018
High Mountain Ranges (1500-2500m)	101	0.06	195	1 286	27 251	3 392	0.9	150	385	3 865	629
Alpine Mountain Ranges (2500-5000m)	4	24.50	56	1 075	4 162	2 058	40.8	204	431	1 274	567

Table 4: Regression results of all Sediment Yield (SY) – Catchment Area (A) relationships. # entries indicates the number of observations, # catch. yr. is the total number of catchment year data, a and b are the regression coefficients of the equation $SY = aA^b$, p indicates the significance level of the exponent (values in italic mean that the equation is insignificant at a significance level of $\alpha=0.05$). The weighted regression section presents the results of the regressions where all observations are weighted according to the square root of their measuring period.

Data Groups		# entries	# catch. yr.	Normal regression				Weighted regression			
				a	b	p	r ²	a	b	p	r ²
I	All data										
I.1	All catchments	1794	29203	167.1	-0.11	<0.001	0.04	160.7	-0.11	<0.001	0.03
I.2	All Gauging Stations	1287	15452	121.1	-0.10	<0.001	0.03	158.2	-0.13	<0.001	0.04
I.3	All Reservoirs	507	13751	193.8	-0.02	<i>0.401</i>	0.00	132.5	0.01	<i>0.535</i>	0.00
I.4	All catchments < 100 km ²	444	8597	114.0	-0.04	<i>0.348</i>	0.00	85.9	0.06	<i>0.179</i>	0.00
I.5	All catchments 100 - 10 000 km ²	1065	16673	440.1	-0.23	<0.001	0.02	673.1	-0.28	<0.001	0.04
I.6	All catchments > 10 000 km ²	285	3933	2293.2	-0.40	<0.001	0.06	952.4	-0.33	0.000	0.05
II	River Catchments										
II.1	Danube	389	4684	254.1	-0.11	<0.001	0.04	264.2	-0.11	<0.001	0.04
II.2	Ebro	23	693	90.7	0.06	<i>0.641</i>	0.01	113.9	0.06	<i>0.681</i>	0.01
II.3	Elbe	58	651	97.8	-0.28	<0.001	0.32	97.5	-0.27	<0.001	0.34
II.4	Oder	25	657	87.9	-0.24	0.009	0.26	170.9	-0.31	0.003	0.33
II.5	Ouse	42	3358	65.6	-0.10	<i>0.223</i>	0.04	46.3	0.05	<i>0.733</i>	0.00
II.6	Po	50	819	244.1	0.01	<i>0.942</i>	0.00	158.5	0.07	<i>0.443</i>	0.01
II.7	Rhine	115	1712	169.9	-0.17	0.001	0.10	397.6	-0.25	<0.001	0.17
II.8	Rhône	58	529	1590.6	-0.28	<0.001	0.38	2242.4	-0.29	<0.001	0.43
II.9	Schelde	40	129	210.8	-0.21	0.013	0.15	255.2	-0.25	0.005	0.19
II.10	Segura	28	1065	116.6	0.07	<i>0.245</i>	0.05	118.5	0.08	<i>0.151</i>	0.08
II.11	Vistula	55	1470	450.6	-0.31	<0.001	0.21	691.2	-0.37	<0.001	0.27
III	All data per Climatic Regions										
III.1	Alpine	157	2267	247.3	-0.09	<i>0.164</i>	0.01	264.3	-0.07	<i>0.329</i>	0.01
III.2	Anatolian	70	1183	102.2	0.02	<i>0.880</i>	0.00	15.4	0.24	0.049	0.06
III.3	Arctic	7	26	45.2	0.42	<i>0.087</i>	0.47	55.5	0.42	<i>0.063</i>	0.53
III.4	Atlantic	282	5668	64.4	-0.13	<0.001	0.10	64.1	-0.11	<0.001	0.09
III.5	Boreal	93	1489	22.1	-0.14	0.001	0.11	27.6	-0.15	0.001	0.12
III.6	Continental	608	9157	170.7	-0.14	<0.001	0.06	238.5	-0.19	<0.001	0.09
III.7	Mediterranean	540	8954	298.0	-0.07	0.007	0.01	247.4	-0.04	<i>0.066</i>	0.01
III.8	Steppic	37	459	2494.7	-0.37	<0.001	0.37	3371.6	-0.37	<0.001	0.38
III	GS-data per Climatic Region										
III.1.GS	Alpine	98	967	183.3	-0.08	<i>0.242</i>	0.01	180.1	-0.04	<i>0.574</i>	0.00
III.2.GS	Anatolian	62	1175	7.5	0.30	0.018	0.09	6.0	0.34	0.006	0.12
III.3.GS	Arctic	7	26	45.2	0.42	<i>0.087</i>	0.47	55.5	0.42	<i>0.063</i>	0.53
III.4.GS	Atlantic	191	939	38.3	-0.08	0.010	0.04	50.6	-0.10	<0.001	0.07
III.5.GS	Boreal	85	1060	23.8	-0.18	<0.001	0.18	28.8	-0.21	<0.001	0.25
III.6.GS	Continental	463	7066	74.4	-0.07	0.017	0.01	131.8	-0.15	<0.001	0.05
III.7.GS	Mediterranean	356	3988	342.6	-0.10	0.003	0.03	310.1	-0.09	0.008	0.02
III.8.GS	Steppic	25	231	1416.5	-0.34	0.006	0.28	1145.0	-0.29	0.035	0.18
III	R-data per Climatic Region										
III.1.R	Alpine	59	1300	389.3	-0.08	<i>0.506</i>	0.01	346.0	-0.06	<i>0.623</i>	0.00
III.2.R	Anatolian	8	8	498.4	0.17	<i>0.358</i>	0.14	498.4	0.17	<i>0.358</i>	0.14
III.3.R	Arctic	0	0	-	-	-	-	-	-	-	-
III.4.R	Atlantic	91	4729	66.6	0.05	<i>0.605</i>	0.00	46.0	0.14	<i>0.183</i>	0.02
III.5.R	Boreal	8	429	357.8	-0.24	<i>0.062</i>	0.47	385.4	-0.24	<i>0.033</i>	0.56
III.6.R	Continental	145	2091	443.4	-0.15	<0.001	0.11	498.5	-0.18	<0.001	0.13
III.7.R	Mediterranean	184	4966	237.7	0.00	<i>0.913</i>	0.00	200.0	0.01	<i>0.780</i>	0.00
III.8.R	Steppic	12	228	42915.1	-0.57	<0.001	0.79	45611.0	-0.57	<0.001	0.80
IV	All data per Topographic Region										
IV.1	Lowland (0-100m)	413	4630	143.5	-0.17	<0.001	0.09	168.1	-0.19	<0.001	0.11
IV.2	Hills (100-500m)	842	14919	112.5	-0.05	0.007	0.01	101.4	-0.05	0.013	0.01
IV.3	Low Mountain Range (500-1500m)	434	7605	198.4	-0.06	<i>0.060</i>	0.01	182.8	-0.04	<i>0.204</i>	0.00
IV.4	High Mountain Range (1500-2500m)	101	1917	168.2	-0.05	<i>0.376</i>	0.01	158.3	-0.03	<i>0.577</i>	0.00
IV.5	Alpine Mountain Range (2500-5000m)	4	132	202.0	0.01	<i>0.979</i>	0.00	310.8	-0.03	<i>0.952</i>	0.00

Table 5: Number of entries for each climatic region (see Fig. 1), subdivided according to the measuring method (gauging station (GS) or reservoir (R)) and topographic zone.

Climatic Zone	Total	Measuring method		Topographic region				
		GS	R	Lowlands	Hills	Low Mnt.	High Mnt.	Alpine Mnt.
Alpine	157	98	59	2	19	75	58	3
Anatolian	70	62	8	0	1	49	19	1
Arctic	7	7	0	0	4	0	0	0
Atlantic	282	191	91	145	134	3	0	0
Boreal	93	85	8	62	29	2	0	0
Continental	608	463	145	72	407	129	0	0
Mediterranean	540	356	184	106	234	176	24	0
Steppic	37	25	12	26	11	0	0	0

Figures:

Fig. 1: Study area and location of all catchment outlets (gauging stations (GS) and reservoir (R)) in the SY-database. Climatic regions were derived from the LANMAP2 database (Mücher et al., 2006; Metzger et al., 2005).

Fig. 2: Cumulative distribution of the gauging stations (GS) and reservoir (R) entries according to the duration of their measuring period.

Fig. 3: Temporal coverage of the entries with a known start and end date ($n = 1490$) according to their measuring method (gauging stations (GS) and reservoirs (R)) (left) and climatic region (right). '# entries' indicates the number of entries in the database that include a certain year in their measuring period.

Fig. 4: Frequency distribution of the number of entries (left) and number of catchment-year data (right) according to catchment area (A). A subdivision is made according the measuring method (top; GS: gauging station, R: reservoir) and according to climatic region (bottom, see Fig. 1).

Fig. 5: Sediment yield (SY) map of Europe based on all gauging station (GS) and reservoir (R) data.

Fig. 6: Cumulative frequency distribution of the SY-values for all data, classified according to climatic region (top, see Fig. 1) and topographic zone (bottom).

Fig. 7: Sediment Yield (SY) – Catchment Area (A) relationships for all data, weighted according to the length of the measuring period (see text). Dashed lines are insignificant at $\alpha=0.05$. I.1: All data, I.2: All gauging station (GS) data, I.3: All reservoir (R) data, I.4: All catchments $< 100 \text{ km}^2$, I.5: All catchments $100 - 10\,000 \text{ km}^2$, I.6: All catchments $> 10\,000 \text{ km}^2$. For details on the regression equations: see Table 4 (weighted regressions).

Fig. 8: Sediment Yield (SY) – Catchment Area (A) relationships, grouped by river catchment and weighted according to the length of the measuring period. Dashed lines are insignificant at $\alpha=0.05$. II.1: Danube, II.2: Ebro, II.3: Elbe, II.4: Oder, II.5: Ouse, II.6: Po, II.7: Rhine, II.8: Rhône, II.9: Schelde, II.10: Segura, II.11: Vistula. For details on the regression equations: see Table 4 (weighted regressions).

Fig. 9: Sediment Yield (SY) – Catchment Area (A) relationships for all data, grouped by climatic region (see Fig. 1) and weighted according to the length of the measuring period. Dashed lines are insignificant at $\alpha=0.05$. III.1: Alpine, III.2: Anatolian, III.3: Arctic, III.4: Atlantic, III.5: Boreal, III.6: Continental, III.7: Mediterranean, III.8: Steppic. For details on the regression equations: see Table 4 (weighted regressions).

Fig. 10: Sediment Yield (SY) – Catchment Area (A) relationships per climatic region (see Fig. 1), subdivided according to measuring method. Circles represent reservoir (R) data; triangles represent gauging station (GS) data. For details on the regression equations: see Table 4 (weighted regressions).

Fig. 11: Sediment Yield (SY) – Catchment Area (A) relationships for all data, grouped by topographic zone of the measuring location and weighted according to the length of the measuring period. Dashed lines are insignificant at $\alpha=0.05$. IV.1: Lowland (0-100m), IV.2: Hills (100-500m), IV.3: Low Mountain Range (500-1500m), IV.4: High Mountain Range (1500-2500m), IV.5: Alpine Mountain Range (2500-5000m). For details on the regression equations: see Table 4 (weighted regressions).