Off-site Impacts and Responses

2.20

Reservoir and Pond Sedimentation in Europe

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2.20.1 INTRODUCTION

One of the most important off-site consequences of soil erosion is the deposition of sediment within reservoirs and ponds. This reduces storage capacity and, consequently, also their useful lifetime. It is estimated that the annual loss in storage capacity of the world's reservoirs due to sediment deposition is around 0.5–1%, and for individual reservoirs these values can be as high as 4–5 % (WCD, 2000). These high rates of storage loss pose a serious threat to the economic sustainability of the reservoir that needs consideration. A detailed inventory on reservoir sedimentation rates exists for the USA (Dendy *et al*., 1973; Dendy and Champion, 1978; Renwick, 1996), but this is lacking for most European countries. Nevertheless, also in Europe, many dams exist and many of the reservoirs face serious sedimentation problems. A report of the World Commission on Dams (WCD, 2000) showed that, at present, there are 5480 large reservoirs in Europe (excluding Russia), with a total capacity of no less than 383.6×10^3 hm^3. The most important reservoir nations in Europe are Spain, France, Italy, the UK, Norway, Albania and Romania. In addition to the larger reservoirs, thousands of smaller

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reservoirs, flood control ponds, irrigation ponds, farm ponds and other man-made water bodies exist throughout Europe. However, no detailed inventory on those smaller sized reservoirs exists at all. For the USA alone, it is estimated that there are at least 2.6 million small, artificial water bodies (Smith *et al.*, 2002), or a density of 0.33 km^{-2}. Although the total density of such small reservoirs may be less in Europe, the total number of such small artificial water bodies can easily be as high as 0.5–1 million (densities of 0.1–0.2 km^{-2}).

All these dams and ponds experience sediment deposition (Figures 2.20.1 and 2.20.2); however, the intensity of the sediment deposition process varies tremendously from one reservoir to the other. Combined, reservoir and pond sedimentation can have an important impact on the sediment dynamics of many river basins in Europe. For the River Ebro, it is estimated that the actual sediment delivery to the delta is only 1 % of the value before the dam construction era (Guillen and Palanques, 1992). As a consequence, marine processes erode the delta, whereas salt seawater intrudes the area. Reduced sediment delivery to larger rivers may also result in river channel incision with various economic and environmental consequences, such as undercutting of infrastructure (e.g. bridges), lowering of the groundwater table in the floodplain and increased soil salinization in floodplain areas and bank collapses, which is, for instance, reported for the River Rhône (Arnaud-Fassetta, 2003) and for several Italian rivers (Surian and Rinaldi, 2003).

Although the impacts of reservoir sedimentation have been illustrated for various European rivers, no effort has been made to give an overview on the spatial variability in reservoir sedimentation rates at the European scale. Although reservoir sedimentation data are a widely used technique to derive sediment yield values for the upstream catchment, such data are very rare. There are several reasons why data on reservoir sedimentation and sediment yield data are hard to find for Europe. First, different types of reservoirs and ponds exist for various reasons (drinking water, power generation, floodwater protection), implying that these are managed by diverse companies and government agencies at local or national levels. For most of these managers,

Figure 2.20.1 Sediment deposition in the large La Fuensanta reservoir, SE Spain. According to Avendaño Salas *et al.* (1997), this reservoir has a storage capacity of 235 hm^3 and experiences a mean annual storage capacity loss of about 0.2 %. Drainage area equals 979 km^2. (Copyright Gert Verstraeten, with kind permission)

Figure 2.20.2 Sediment deposition in a small flood retention pond in Belgium. It has a storage capacity of 10 000 m^3 and a mean annual storage capacity loss of nearly 10 %. Drainage area equals 48 km^2 (data from Verstraeten, 2000). (Copyright Gert Verstraeten, with kind permission)

sedimentation may be problematic but not important enough to measure it accurately. If it is measured, often only sediment volumes are reported, which is important for managing the reservoir, but not enough for calculating sediment yield. The lack of data is even more pronounced for smaller ponds operated by government agencies. In some cases, especially for private companies, high sedimentation rates are being kept secret as confidential information. Finally, the lack of a single European agency that coordinates all information on soil erosion and reservoir sedimentation, comparable to the National Resources Conservation Service (NRCS) in the USA with the RESIS database (Reservoir Sedimentation Information System), hampers a better understanding of reservoir sedimentation in Europe. This paper brings together sedimentation data for nearly 400 European reservoirs and ponds from various sources. This dataset was used to calculate and analyse the spatial variability of sediment delivery in various European countries. Furthermore, the impact of man-made reservoirs and ponds on sediment delivery at the continental scale is discussed.

2.20.2 SEDIMENTATION RATES IN EUROPEAN RESERVOIRS AND PONDS

Data used in this analysis were taken from sources reported in Table 2.20.1. Table 2.20.2 provides generalized data on sedimentation rates for 392 reservoirs and ponds in a number of European countries. Mean annual volumetric sedimentation rates for all studied reservoirs and ponds are shown in Figure 2.20.3. It should be noted, however, that the size and type of the reservoirs and ponds studied differ greatly from country to country, making it difficult to compare the results. For instance, for Belgium, only data for very small flood-control ponds are analysed, whereas for Spain only larger reservoirs have been studied (see also Figures 2.20.1 and 2.20.2).

TABLE 2.20.1 Data sources on reservoir and pond sedimentation used in this study

Country	Data source
Austria	Cyberski, 1973; Tschada and Hofer, 1990
Belgium	Verstraeten and Poesen, 2001a; Verstraeten, 2000
Czech Republic	Krasa *et al*., 2005; Van Rompaey *et al*., 2003a; Cyberski, 1973
France	Cadillon *et al*., 1981; Combes, 1981; Fauroux, 1981; Vivian and Thomas, 1982; Cravero and Guichon, 1989; Blanc *et al*., 1989; Brochot, 1993
Germany	Baade, 2001. Cyberski, 1973; Schröder and Theune, 1984
Italy	Bazzoffi, 1987; Bazzoffi *et al*., 1996; Bazzoffi and Van Rompaey, 2004; Tamburino *et al*., 1989, 1990; Van Rompaey *et al*., 2003b
Poland	Cyberski, 1973; Lajczak, 1996, 2003
Romania	Ionita *et al*., 2000; Rãdoane and Rãdoane, 2005
Slovakia	Janský, 1992; Cyberski, 1973
Spain	Avendaño Salas *et al*., 1997a,b; Verstraeten *et al*., 2003; Cobo Rayán, personal communication
Switzerland	Beyer Portner, 1998
UK	Al-Jibburi and McManus, 1993; Barlow and Thompson, 2000; Butcher *et al*., 1992, 1993; Charlesworth and Foster, 1993; Curr, 1995; Duck and McManus, 1990; Foster, 1995; Foster *et al*., 2003; Foster and Walling, 1994; Foster and Lees, 1999; Labadz *et al*., 1991; McManus and Duck, 1985; White *et al*., 1996

To overcome this problem partly, we relate the annual loss in storage capacity to the ratio of capacity to catchment area (Figure 2.20.4). For 40 out of the 392 reservoirs and ponds, no storage capacity data are known and, consequently, no annual losses in storage capacity could be calculated. The highest storage capacity losses (>5 %) are found in the smaller ponds of central Belgium, in various medium-sized Alpine reservoirs (especially in south-east France) but also in some larger reservoirs in the Romanian Carpathians. Lowest annual storage capacity losses (<0.1 %) are found for the very large reservoirs with relatively small drainage areas (such as some Swiss reservoirs in the higher Alps, e.g. Grande Dixance) and for the medium-sized reservoirs in the UK.

Table 2.20.3 provides mean and total figures on reservoir sedimentation for the analysed reservoirs. The average annual storage capacity loss for 352 reservoirs is 0.26 %, which corresponds to a total measured sedimentation rate of 62.65 $hm^3\ yr^{-1}$. The total sedimentation rate in all European reservoirs and ponds will be much higher. For Spain alone, Batalla (2002) estimated the total annual sedimentation rate in all large reservoirs at 170 $hm^3\ yr^{-1}$. He used a mean annual storage loss of 0.3 %, a value that corresponds to the median storage loss of the 87 Spanish reservoirs in this study (Table 2.20.1), and applied this to all the large reservoirs in Spain (around 1200). By extrapolating the mean annual storage loss of 0.26 % to all the 5480 large reservoirs in Europe having a total storage capacity of $384 \times 10^3\ hm^3$ (WCD, 2000), we can assess the total sedimentation rate in large European reservoirs at 997 $hm^3\ yr^{-1}$ (Table 2.20.3). A similar figure of 1074 $hm^3\ yr^{-1}$ was obtained applying the size distribution of observed reservoirs to all 5480 large reservoirs in Europe and using mean observed storage losses for 10 reservoir size classes (Table 2.20.4). The size distribution of the 352 studied reservoirs corresponds more or less to the size distribution of the 5480 reservoirs according to the World Commission on Dams (WCD, 2000).

These figures do not include sedimentation in smaller reservoirs and ponds, which can have the same order of magnitude. For the USA, Smith *et al.* (2002) estimated that half of the sediment storage in water bodies was trapped in large reservoirs and the other half in smaller reservoirs and ponds. For Europe, insufficient

TABLE 2.20.2 Reservoir and catchment characteristics for 392 reservoirs and ponds in 12 European countries

Country	No. of reservoirs with data	Catchment area (km^2)			Capacity (10^3 hm^3)			Annual sedimentation rate (% of storage capacity)			Reservoir sedimentation rate (m^3 km^{-2} yr^{-1})			Total sedimentation rate (hm^3 yr^{-1})
		Median	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.	
Belgium	21	8	0.1	48.7	0.008	0.0001	0.025	8.20	2.30	28.60	111	18	955	0.022
Czech Republic and Slovakia	36	13	0.8	412.0	0.106	0.017	0.288	1.76	0.32	9.29	150	4	442	0.086
UK	64	5	0.4	54.4	0.622	0.006	21.4	0.09	0.00	1.76	138	2	1075	0.132
Italy	53	68	0.3	697.0	6.69	0.007	325	0.68	0.00	14.35	497	1	2754	4.441
Spain	87	690	1.3	16952.0	420	1.8	1670	0.30	0.00	4.43	231	1	6581	24.631
Romania	59	542	33.2	19445.0	13.3	0.22	1400	1.49	0.04	13.71	213	6	3208	21.670
France	8	990	3.6	4850	14.7	0.12	1272	3.37	0.90	10.00	240	8	2708	3.482
Switzerland	19	49	16.6	886.9	20.15	0.04	401	0.19	0.01	95.37	475	44	2048	1.749
Austria	7	324	10.0	6250	0.845	0.15	140	10.25	0.01	100	262	37	1851	1.233
Germany	15	30	0.6	1423	–	–	–	–	–	–	35	7	154	0.486
Poland	23	1124	94.0	193900	94.3	8	474.5	0.13	0.01	0.83	129	2	1191	5.155
Total	392		0.1	193900		0.0001	1670		0	100		1	6581	63.087

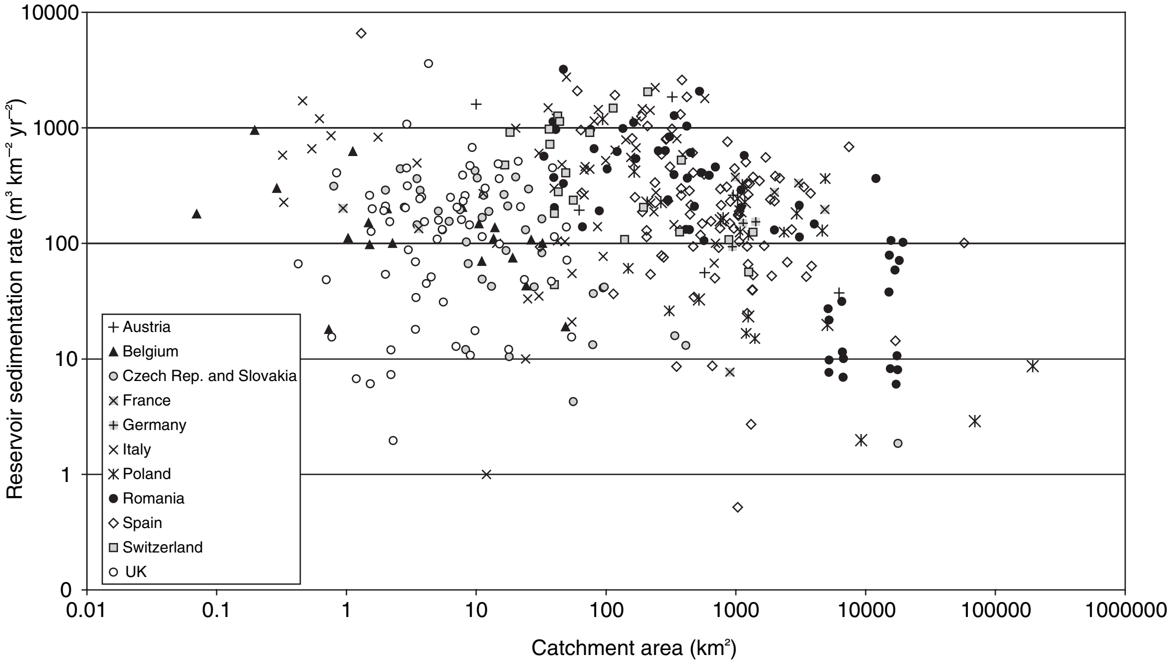

Figure 2.20.3 Mean annual volumetric reservoir sedimentation rates versus catchment area for 392 ponds and reservoirs in 12 European countries

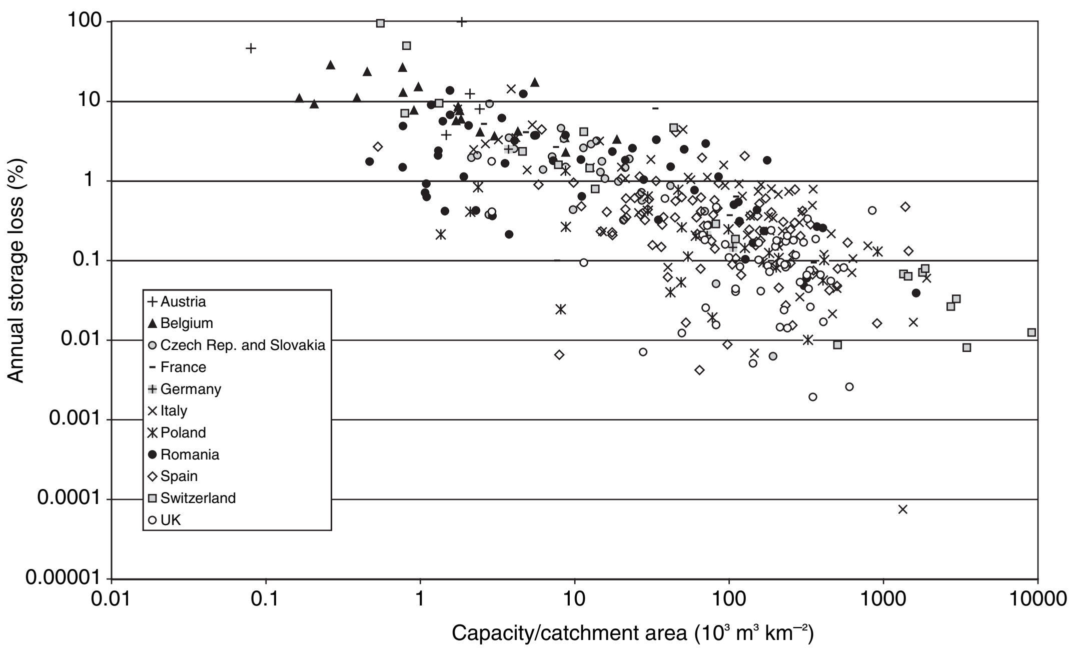

Figure 2.20.4 Annual storage loss versus a capacity to catchment area ratio for 352 ponds and reservoirs in 12 European countries

TABLE 2.20.3 Estimation of total annual sedimentation rate in all 5480 large European reservoirs using mean annual storage capacity loss of 352 studied reservoirs

	This study	Europe
Total No. of reservoirs	352	5480
Total reservoir capacity (hm^3)	24466	383600
Total annual sedimentation volume ($hm^3\ yr^{-1}$)	62.65	997.36
Mean annual storage capacity loss (%)	0.26	0.26

information is available on pond sedimentation rates in various regions. Most of the smaller ponds for which data are available are situated in the loess belt of central Belgium, which is characterized by moderate to high erosion rates (Chapter 1.30). If we assume that their mean annual storage loss of 10 % is representative for the 0.5–1 million ponds in Europe, mean annual sedimentation rates could indeed be as high as 500–1000 $hm^3\ yr^{-1}$. However, if it is assumed that most ponds are situated in regions with lower erosion rates, these values can be much lower, even less than 100 $hm^3\ yr^{-1}$. Total sediment storage in all European reservoirs and ponds therefore probably ranges from 1000 to 2000 hm^3/year. It is clear that smaller ponds can be an important sediment sink in the total sediment budget of large European river systems, but more data on sedimentation rates for smaller ponds are needed to obtain a reliable estimate.

Data for the 5480 large reservoirs are for the whole of Europe excluding the Russian Federation. This corresponds to a total land area of approximately $5.57 \times 10^6\ km^2$. Hence the mean annual sedimentation rate in larger European reservoirs corresponds to about 180 $m^3\ km^{-2}\ yr^{-1}$ or 1.8 $m^3\ ha^{-1}\ yr^{-1}$. Adding the sedimentation rates in smaller ponds, this value will probably range between 2 and 4 $m^3\ ha^{-1}\ yr^{-1}$.

2.20.3 COMPUTING SEDIMENT YIELD FROM RESERVOIR SEDIMENTATION RATES

Reservoir and pond sedimentation rates are one of the most often used means to assess sediment yield worldwide (Dendy *et al.*, 1973; McManus and Duck, 1985; Van den Wall Bake, 1986; Neil and Mazari, 1993; Foster, 1995; White *et al.* 1996; Verstraeten and Poesen, 2001a). Area-specific sediment yield (*SSY*, $t\ km^{-2}\ yr^{-1}$) can be calculated using

$$SSY = 100 \frac{SV \times dBD}{TE \times A} \qquad (2.20.1)$$

where *SV* is the annual sedimentation rate in the reservoir of pond ($m^3\ yr^{-1}$), *dBD* the dry sediment bulk density ($t\ m^{-3}$), *TE* the sediment trap efficiency of the reservoir or pond (%) and *A* the catchment area (km^2) draining to the reservoir or pond. The advantage of reservoirs and ponds for the study of sediment yield is that they are abundant, which makes it possible to study sediment yield at a regional scale. Furthermore, reservoirs and ponds also trap bedload sediment. This type of sediment is rarely measured, although it can be very important, certainly in Mediterranean Europe and in mountainous regions.

However, every parameter in Equation (2.20.1) needs to be estimated and this is not always possible, thereby making the sediment yield assessment less accurate (e.g. Salas and Shin, 1999; Evans and Church, 2000; Verstraeten and Poesen, 2002). Many studies that report on reservoir sedimentation rates were not performed with the goal of calculating sediment yield, and therefore not all the necessary information to apply Equation (2.20.1) is known. Especially values for *dBD* and *TE* are rarely provided. Furthermore, if values for

TABLE 2.20.4 Estimation of total sediment deposition values in all large 5480 European reservoirs using size distribution and mean annual storage capacity losses of 352 studied reservoirs

Minimum capacity (hm^3)	Maximum capacity (hm^3)	Median capacity (hm^3)	No. of studied reservoirs and ponds	Estimated number of reservoirs in Europe	Mean annual storage capacity loss for studied reservoirs and ponds (%)	Total measured annual storage loss for studied reservoirs and ponds (hm^3)	Total estimated annual storage loss for studied reservoirs and ponds (hm^3)[b]	Total estimated annual storage loss for all European reservoirs (hm^3)[c]
0	0.01	0.005	13	202	10.07	0.005	0.007	0.10
0.01	0.1	0.05	29	451	4.95	0.05	0.08	1.23
0.1	0.5	0.25	50	778	4.65	0.57	0.70	10.86
0.5	1	0.75	19	296	5.86[a]	0.84	0.84	13.00
1	5	2.5	41	638	1.79	1.93	2.20	34.28
5	10	7.5	30	467	1.42	3.24	3.20	49.74
10	50	25	84	1308	0.99	20.08	24.95	388.40
50	100	75	25	389	0.26	4.53	4.88	75.89
100	500	250	54	841	0.15	18.39	24.30	378.31
500	1000	750	7	109	0.15	13.00	7.88	122.60
Total			352	5480	0.26	62.65	69.01	1074.40

[a]Only 1.73 % if one Alpine reservoir with an annual storage capacity loss of 100 % is left out; this has no major influence on total sedimentation values, however.
[b]Mean annual storage capacity multiplied with number of studied reservoirs and the median capacity (e.g. $13 \times 0.005 \times 0.1007 = 0.007$).
[c]Mean annual storage capacity multiplied with number of estimated reservoirs and the median capacity (e.g. $202 \times 0.005 \times 0.1007 = 0.10$).

TABLE 2.20.5 Statistics on sediment yield data derived from reservoir and pond sedimentation rates

		Area-specific sediment yield ($t\,ha^{-1}\,yr^{-1}$)		
Country	No. of reservoirs with data	Median	Min.	Max.
Belgium	21	2.3	0.4	20.6
Czech Republic and Slovakia	36	2.2	0.1	7.0
UK	71	0.5	0.0	3.8
Italy	53	4.5	0.0	25.1
Spain	65	2.9	0.0	26.8
Romania	59	5.4	0.1	46.8
France	6	4.0	2.8	50.5
Switzerland	19	7.8	0.6	31.4
Germany	12	0.7	0.2	2.0
Poland	18	2.6	0.1	17.2

dBD or *TE* were used to apply Equation (2.20.1), they are often estimated using standard procedures developed for large reservoirs in the USA, but actual measurements are rare (see Verstraeten and Poesen, 2001b, and Verstraeten and Poesen, 2000, for more information on *dBD* and *TE* predictions, respectively). This seriously hampers the use of volumetric sedimentation rates (*SV*) to assess sediment yield.

Statistics on area-specific sediment yield rates in Europe based on 372 reservoirs and ponds are given in Table 2.20.5. In most cases, no reliable measurement of *TE* or *dBD* was made. In those cases, *TE* was estimated using the equation of Brown (1943), which has proven to be useful for UK reservoirs (Butcher *et al.*, 1992) and reservoirs in Spain (Avendaño Salas *et al.*, 1995). When no information was presented on reservoir capacity, *TE* was set at 100 %, such that a minimal sediment yield was estimated. Estimates for *dBD* were based on *dBD*-measurements of nearby reservoirs with similar sediments. If such information was not available, *dBD* was set at $1\,t\,m^{-3}$.

2.20.4 SPATIAL VARIABILITY OF SEDIMENT YIELD IN EUROPE BASED ON RESERVOIR SEDIMENTATION DATA

Calculated area-specific sediment yields are plotted against catchment area in Figure 2.20.5. A large scatter can be observed, illustrating that for the whole of Europe no significant relation between area-specific sediment yield and catchment area can be established. This large observed variability in area-specific sediment yield for catchments with similar sizes is due to the heterogeneity of the European landscape in terms of climate, topography, lithology and land cover. At the level of individual countries, some significant relations can be drawn, however (Figure 2.20.6). This is the case for Belgium, the Czech Republic and Slovakia, Spain, France, Poland, Romania and Germany. Within Italy, Switzerland and the UK, the variability is still too high to obtain a significant relationship. It should also be realised that part of the variability can also be attributed to errors in the calculation of the *SSY* owing to, for instance, erroneous estimations of *dBD* and/or *TE*. Furthermore, the period for which the *SV* is measured may differ from reservoir to reservoir, which can make a comparison difficult if controlling factors such as climate or land use have changed from one period to another.

Despite these uncertainties, it is evident from Figures 2.20.5 and 2.20.6 that two major regions in Europe can be distinguished with respect to area-specific sediment yield. The first group of countries includes Belgium, Germany, the UK, Czech Republic, Slovakia and part of Italy. A second group includes Romania,

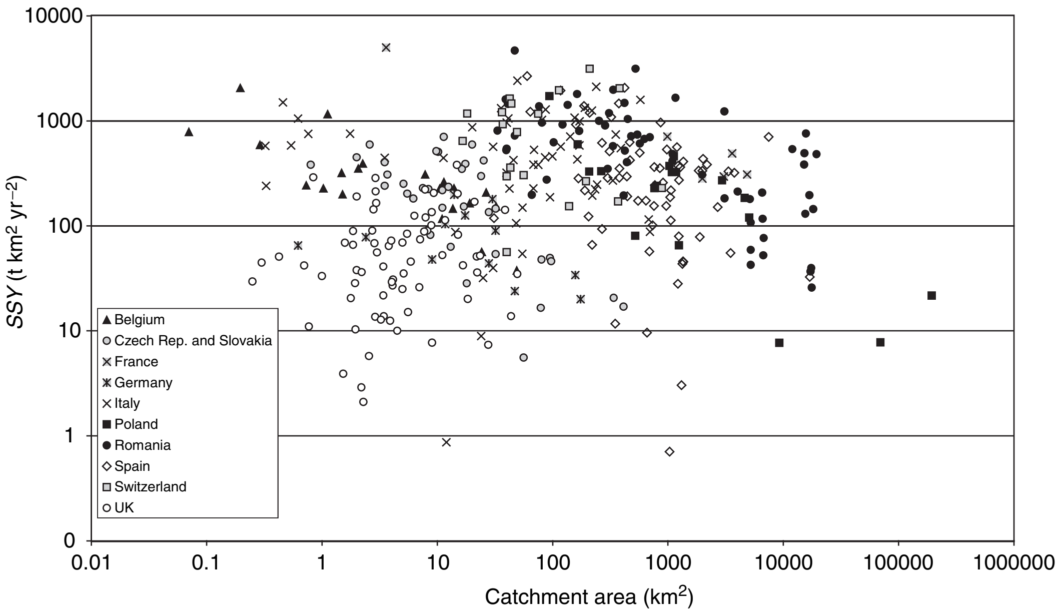

Figure 2.20.5 Area-specific sediment yield (*SSY*, $t\,km^{-2}\,yr^{-1}$) plotted against catchment area (km^2) based on sedimentation rates for 372 reservoirs and ponds in 11 European countries

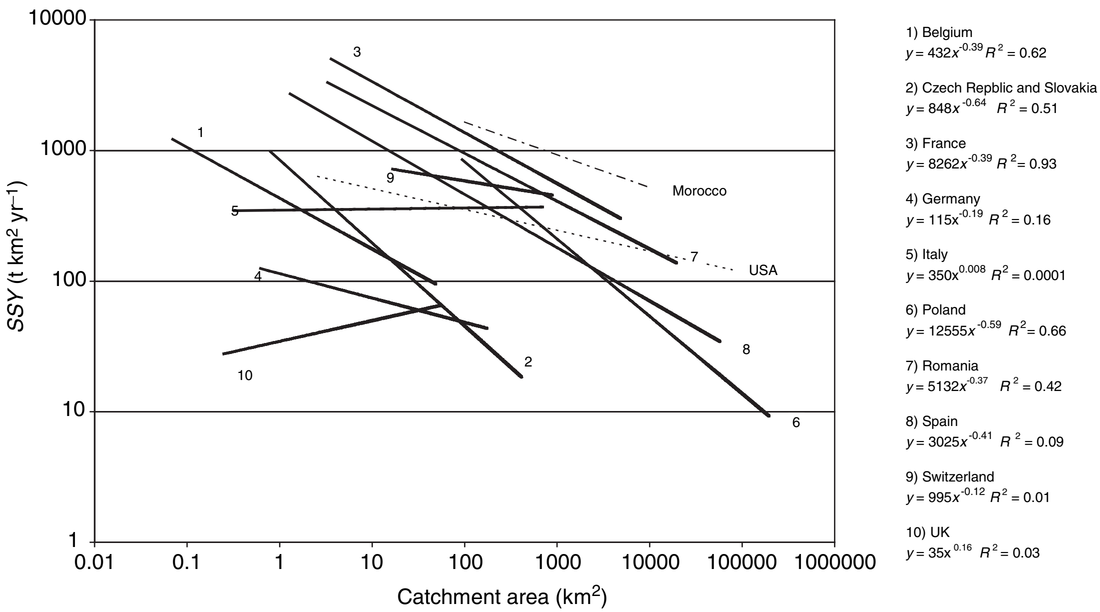

Figure 2.20.6 Relation between catchment area and area-specific sediment yield (*SSY*) for 11 European countries based on reservoir sedimentation rates and compared with similar relations for the USA (Dendy and Bolton, 1976) and Morocco (Lahlou, 1988). Regressions are significant at the 95 % confidence level for all countries except for the UK, Italy and Switzerland

Spain, France, Poland, Switzerland and the other part of Italy. For a given catchment area, area-specific sediment yield values are much lower for the first than the second group of countries.

The first group encompasses regions in the north-western and central European lowlands and tectonically old middle mountains. Topography is less pronounced in these regions with a majority of gentle slopes. In many of the studied areas pasture and forest dominate (e.g. UK and Germany), whereas in other areas cropland is the dominant land use (e.g. Belgium, Slovakia). Highest area-specific sediment yield values in group 1 are observed for catchments in central Belgium with a rolling topography, highly erodible loess-derived luvisols and intensive agriculture. Lowest area-specific sediment yield values in group 1 are observed for forested catchments in the UK Midlands.

The second group are data from regions which are either dominated by mountainous topography (Carpathians in Poland and Romania, south-east Alps in France, Alps and Apennines in Italy, Pyrenees and several Sierras in Spain and the Alps in Switzerland) or that are situated in the Mediterranean region (south-east France, Spain, central and southern Italy, including Sicily), or a combination of the two. Mediterranean regions are generally more prone to erosion and sediment transport owing to the higher rainfall erosivity, sparse vegetation cover and often a highly erodible lithology (e.g. marls). Highest area-specific sediment yield values in group 2 are observed for very steep mountain catchments in Mediterranean France, where the importance of torrential flows is very high, whereas lowest area-specific sediment yield values are seen for the very large catchments in Poland that drain the Carpathians but also encompass large parts of the lowlands at the foot of the Carpathians that do not contribute much sediment. In fact, the larger catchments in Poland should be classified to group 1 and only the catchments situated totally in the Carpathians are part of group 2.

Milliman (2001) made a similar distinction between these two regions when he compared the suspended sediment load data from large rivers in northern and southern Europe. The lowest suspended sediment loads were found for Scandinavian rivers, mainly because of the dominance of older and harder rocks. However, no dataset on reservoir sedimentation rates for Scandinavian countries is available Figure. 2.20.6 also compares the area-specific sediment yield data for Europe with data from the USA and Morocco. It is clear that the median area-specific sediment yield in Europe is more or less comparable to the median trendline observed for 800 reservoirs in the USA (Dendy and Bolton, 1976). The relation for Morocco (Lahlou, 1988) is in accordance with the relations for European Mediterranean countries, which show similar climatic and geomorphological characteristics. The fact that the Moroccan catchments have even more pronounced topography and less vegetation (more arid than Europe) may explain the even higher area-specific sediment yield values than for Spain.

Although there is a clear contrast between Mediterranean regions and north-western and central European regions, variability within every country and region remains high. In Spain, for instance, area-specific sediment yield values for a catchment of 1000 km^2 may vary between less than 1 to more than 1000 $t\,km^{-2}\,yr^{-1}$. This can be attributed to important regional differences in topography (the Sierras versus relatively flat intramontane basins), geology (marls versus limestone) and the presence of gullies as sediment source but certainly as sediment pathways increasing the connectivity from the hillslopes to the reservoirs (Verstraeten *et al.*, 2003; Poesen *et al.*, 2003). The highest values for Spain correspond to the trendline for Moroccan reservoirs. These catchments are characterised by the presence of many gullies and low vegetation cover.

For the moment, insufficient data on factors controlling sediment yield (e.g. topography and land use) are available for the corresponding catchments to investigate the spatial variability in a more detailed way.

The high variability in sediment yield is also illustrated in Figure 2.20.7. Although there is a strong significant relation between catchment area and total annual sediment yield, this is only related to catchment area itself (area exponent equals $\sim$1). A huge scatter around the mean trend exists, making it impossible to use this relation to predict the sediment yield in Europe. For instance, there is a 95 % probability that a catchment of 100 km^2 yields a total sediment delivery in between 1000 and 600 000 t.

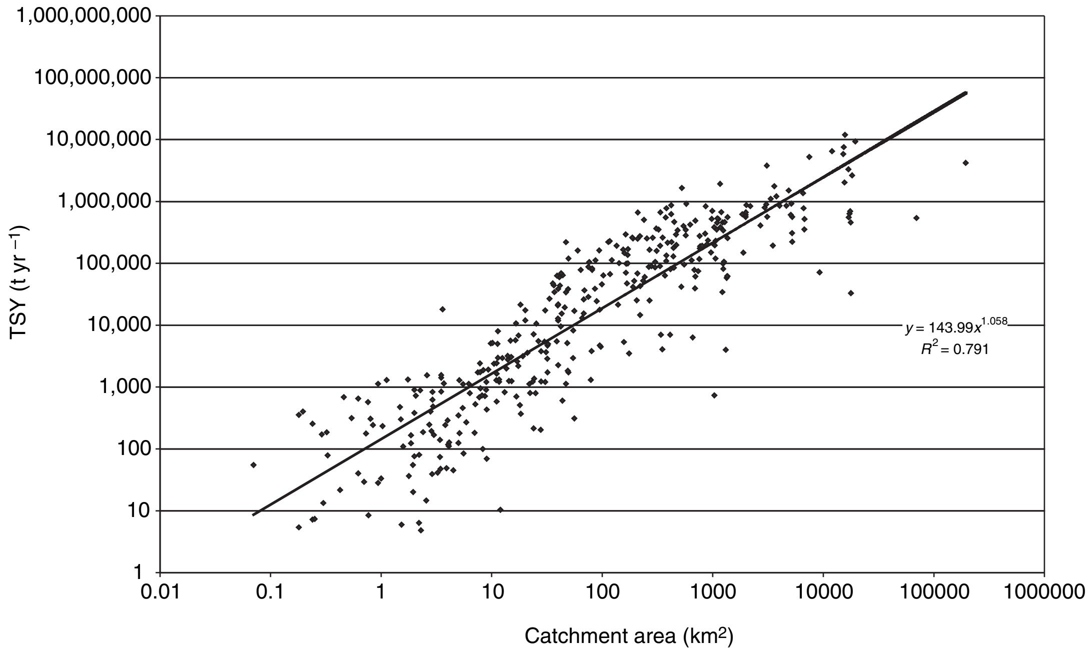

Figure 2.20.7 Total annual sediment yield (*TSY*) versus catchment area for 372 reservoirs and ponds in 11 European countries. Dotted lines represent the 95 % confidence limits for individual predictions of total annual sediment yield

For smaller catchments (and smaller corresponding ponds), there is also a very important temporal variability in sediment yield that makes it difficult to obtain reliable long-term estimates of the sediment yield using sedimentation rates. This is probably best illustrated with sedimentation rates for three small ponds in the Massif des Maures, south-east France. In the first year after a forest fire, sediment deposition rates in small ponds with catchments of 18, 24 and 94 ha reached extreme values of 19.7, 10.6 and 12.0 t ha^{-1} yr^{-1}, respectively. The year after, however, sediment yields dropped to 0.3 t ha^{-1} yr^{-1} in all three catchments (Martin *et al.*, 1997). Another example was the complete filling of a small flood-control pond in central Belgium after a local intense storm event. This raised the mean annual area-specific sediment yield over a 3-year measurement period from 8.4 to 20.1 t ha^{-1} yr^{-1} (Verstraeten, 2000).

2.20.5 IMPACT OF RESERVOIRS AND PONDS ON TOTAL SEDIMENT YIELD AT THE EUROPEAN SCALE

It is not possible to estimate the total and mean sediment yield for Europe based on the reservoir data. Especially for Spain and Romania, many dams are located above each other on the same river. Summing the area-specific sediment yield values for reservoirs on the same river would overestimate the true area-specific sediment yield for that river basin. However, a minimum sediment yield can be assessed if only the sediment deposits in the reservoirs are taken into account, and no correction for *TE* is made. For 356 out of the studied reservoirs and ponds, this corresponds to a total value of 56.3 hm^3 yr^{-1} and 70.5 Mt yr^{-1}, thus resulting in a mean *dBD* of 1.25 t m^{-3} (70.5/56.3). Above, we estimated the total annual deposited sediment volume in all

European reservoirs and ponds at 1000–2000 $hm^3 yr^{-1}$ or 200–400 $m^3 km^{-3} yr^{-1}$. Multiplying this with the mean *dBD* for the studied reservoirs and ponds, a minimum area-specific sediment yield of 250–500 $t km^{-2} yr^{-1}$ can be established, corresponding to 1250–2500 $Mt yr^{-1}$. These are rather high values compared with estimates of total sediment delivery from European rivers to the Atlantic Ocean, the Mediterranean Sea and the Black Sea. Milliman and Meade (1983) estimated this at 230 $Mt yr^{-1}$ or 50 $t km^{-2} yr^{-1}$ (total surface area $4.61 \times 10^6 km^2$) based on limited suspended sediment load data for several rivers near their mouth. Although the figures reported by Milliman and Meade (1983) are conservative estimates (they are often based on infrequent suspended sediment sampling that mostly underestimates total sediment load), it is clear that reservoirs and ponds have an enormous impact on the sediment budget for European rivers at the subcontinental scale. All reservoirs and ponds thus trap 5–10 times the amount of sediment that is eventually delivered to the sea. This would correspond to a mean sediment trap efficiency of 80–90 % at the European scale. These estimates are much higher than those given by Vörösmarty *et al*. (2003), who estimated the mean trap efficiency for 88 very large reservoirs (i.e. capacity $>$500 hm^3) for the whole of Europe at 23 %. They did not estimate the contribution of other large reservoirs [i.e. the 5480 reservoirs according to the WCD (2000) minus the very large reservoirs] to total trap efficiency at the European scale. However, on the global scale, Vörösmarty *et al*. (2003) estimated the trap efficiency of very large and large reservoirs at 16 and 12 %, respectively. Using the same ratio between very large and large reservoirs, the impact of all large and very large reservoirs in Europe would be of the order of 40 %. The calculations by Vörösmarty *et al*. (2003) were only based on the hydrological impact that reservoirs have by increasing the residence time, but do not take into account spatial variability in sediment yield. Since the highest sediment yields are found in those European countries with the highest number of reservoirs (Spain, Italy, Romania), they underestimate the true sediment trap efficiency, which is confirmed by the analysis in this study. Furthermore, Vörösmarty *et al*. (2003) do not take into account the impact of the smaller reservoirs. It is clear from the analysis made in this study that reservoirs and ponds have a major impact on sediment delivery at the European scale, probably the most important anthropogenic impact on sediment dynamics that there is.

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