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A review of the measurement of sediment yield in different scales

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Resumo

A presente revisão tem como objetivo apresentar e discutir, sucintamente, o estado da arte em termos de medições de produção de sedimentos. Cerca de 80 publicações foram consultadas, representando todos os continentes e mais de 30 países. Observa-se que a medição da produção de sedimentos é mais dependente da resolução temporal que da espacial. A produção de sedimentos média de 364 bacias é analisada e apresentada. Dados globais não apresentam tendência, em relação à área da bacia, e o mesmo pode ser afirmado para os diversos continentes, exceto para a África, que apresenta decréscimo consistente da produção de sedimentos com a área da bacia. Apresenta-se, graficamente, a aplicabilidade de técnicas de medição da produção de sedimentos em função da área e do período de avaliação.

Palavras-chave: Produção de sedimentos, erosão, experimento, revisão da literatura.

Abstract

The present review paper has the objective of presenting and briefly discussing the state-of-the-art papers on sediment yield (SY) measurement. About 80 publications are referred to, representing all continents, and more than 30 countries. It is observed that SY measurement technique is a much stronger function of temporal than of spatial resolution. Annual average SY data of 364 catchments are summarized. Global data presents no trend concerning catchment area and the same behavior is observed for the continents, except for Africa, which presents a consistent decrease of SY with increasing area. A graphical representation of the spatial and temporal applicability of the different SY measurement techniques is shown.

Keywords. *Sediment yield, erosion, experiment, literature review.*

1. Introduction

Erosion, sediment transport and sediment deposition are major environmental issues that affect society through reduction of reservoir capacity and intensification of both water pollution and floods (Williams, 1975; Walling, 1983; Lane et al., 1997; van Rompaey et al., 2001; Zartl et al., 2001; Fasching & Bauder, 2001, Nelson & Booth, 2002, Abril & Knight, 2004). Sediment yield (SY) is defined as the sediment discharge through a certain river section per unit catchment area per unit time (ASCE, 1982).

Although some specific areas have abundant SY data (e.g. Wasson, 1994; Krishnaswamy et al., 2000), several researchers complain about the lack of reliable long-term SY data (Wilson, 1977; Lal et al., 1977; Walling, 1983; Gergov, 1996; Kidron, 2001, Zarris et al., 2002). Goodrich & Woolhiser (1991, p.205) refer to Hydrology as a "data poor science". Without a representative SY database, the effort expended on modelling is less effective, since validation is not possible (Ferro & Porto, 2000). In agreement with this, Verstraeten & Poesen (2001b, p.83) proposed the "establishment of a sediment yield database for larger areas". Grayson et al. (1992, p.2663) concluded that one of the reasons for the lack of field data is the low "publication-to-effort ratio" in experimental researches, whereas it is "cheaper and easier" to perform "computer simulations using other people's data".

2. Relevant review papers

Laronne & Mosley (1982) presented a state-of-the art review on erosion and SY, and Walling (1983) discussed the limitations of the sediment delivery ratio concept (SDR, ratio between sediment yield and gross erosion). Foster et al. (1990) suggested that short-term hydro-sedimentological processes could be monitored by direct measurements, medium-term processes by reservoir surveys, and long-term processes by palaeo-hydrological investigation. Goodrich & Woolhiser (1991) reviewed several aspects of catchment hydrology, including SY, for different spatial scales (0.01-500 km^2), and stressed the need to undertake large-scale field experiments and to improve our understanding of climate change impacts (see Verstraten & Poesen, 2001a; Figueiredo & Bathurst, 2002). Milliman & Syvitski, (1992) studied sediment contributions of important rivers in several continents, analysing their differences. Lane et al. (1997) presented a discussion on the processes controlling SY in several spatial scales. Huang (1999) and Cao & Knight (1999a) presented Internet literature research on soil erosion modelling and measurement. Cao & Knight (1999b) listed the state-of-the-art papers on river systems and basins, including related papers on erosion, sediment transport and deposition.

3. Short-term response measurements

Nearing et al. (1997) studied the hydraulics of rills due to their importance as sediment sources. Considering the small scale of their experimental field, rill width evolution was monitored by micro-morphological measurements, using rulers. Bochet et al. (2000) researched mound development in Spanish semiarid region, analysing the plants-sediment interaction processes with a two-dimensional micro-profilemeters; identifying the most efficient plants for sediment retention; and recommending their use in forestation programmes to combat desertification.

Planchon et al. (2000) monitored three 50 m^2 plots in Senegal during five days to investigate erosion and spread of Nematodes. Erosion was estimated using the micro-morphologic (relief-meter) and the sediment-load approaches. Gaskin & Gardner (2001) investigated the impact of cryptograms (soil surface plant communities) on runoff and erosion in monsoonal Himalaya using 200 events in micro-erosion plots of 2m^2. They concluded that cryptograms and weeds reduced soil losses by 50% on average, which is relevant in plots that yield up to 3,600 $ton.km^{-2}.a^{-1}$.

Robichaud & Waldrop (1994) studied the effect of site preparation burning on SY. The experiments were conducted under low-severity and high-severity site conditions, with monitoring of runoff and sediment concentration, and showed that decreasing soil initial moisture resulted in increasing burn severity, in decreasing infiltration and in increasing SY: high severity experiments yielded forty times more sediment then low severity ones.

Kidron & Yair (2001) studied runoff and erosion events from 1990 to 1994 in the Negev Desert in plots up to 1,643 m^2 monitoring water discharge and sediment concentration. Despite the low rainfall annual rate (95 mm, 10-20 events per year), runoff and SY (22 $ton.km^{-2}.a^{-1}$) occurred due to the presence of a thin (1-3 mm) microbiotic crust, mostly composed of cyanobacteria. Kidron (2001) used the same experimental facility to research the sediment enrichment with organic matter.

McConkey et al. (1997) analysed the inter-annual SY variability in semiarid Canada (5 ha) using an event-based approach. They concluded that 86% of soil loss occurred within one month (16 March - 15 April), and that erosion was less intense in semiarid than in sub-humid Canada. Ferro & Porto (2000) measured SY response to 140 rainfall events in three experimental basins in Italy (areas below 2 ha) over a 17-year period. The average SY in the small catchments was 430 $ton.km^{-2}.a^{-1}$.

Kinnell (1997) studied runoff and erosion based on 190 events between 1963 and 1968 in two plots in Australia monitoring runoff and sediment concentration (rill and inter-rill). Fasching & Bauder (2001) investigated the question of SY reduction by vegetative filter strips, measuring 24-hour irrigation events in nine 74-m^2 plots in semiarid USA. Results showed effectiveness of vegetative filter strips at reducing sediment concentration up to 68% and their use for short-term erosion mitigation was recommended.

Several researchers monitored watersheds, not just plots, in order to understand SY short-term responses, using the runoff sediment-concentration approach. Williams & Berndt (1972) used 17 years of data (from 1940 to 1970) from Brushy Creek watershed, USA. Williams (1975) divided the experimental watershed into sub-watersheds (3-5 km^2) to measure SY for daily events so as to understand sediment routing. Khanbilvardi & Rogowski (1984) relied on a 10-year SY data series of a 1.95-km^2 watershed to analyse daily sediment response to rainfall. Zhanbin et al. (1999) studied the Loess Plateau in China by monitoring rainfall events in the Wangdaohenta station (1977-1989). Rius et al. (2001) studied the influence of watershed characteristics and management on reservoirs using data (including bed-load measurement) from three experimental nested basins (2.6, 65.2 and 222.5 km^2) in semiarid Spain. Because Andes Mountains are subject to severe flash floods, Braud et al. (2001) instrumented two catchments at three scales (local, slope and watershed) in the arid Argentinean Andes to assess rainfall effects on runoff and on SY, which is achieved after analysis of data from 50 events in 11 years. Rainis et al. (2002) estimated event SY in a small basin in Malasya and its relationship with rainfall intensity. Sivakumar (2002) studied the prediction of suspended sediment concentration in rivers, using daily suspended-sediment concentration and discharge data from the Mississippi river basin. Zhu et al. (2002) investigated 117 events (1956-1970) in a small semiarid basin (0.22 km^2) in China, so as to quantify tunnel erosion and its impact on SY. Van Rompaey et al. (2001) measured SY in 21 catchments in central Belgium using three measurement approaches, depending on the size of the catchment: erosion and deposition volumes assessment in catchments, suspended load monitoring in rivers, and morphologic surveys in sediment retention ponds.

4. Medium-term response measurement

Water resources management requires SY information in order to construct and apply sustainable watershed policies. For such purposes, medium-term responses ranging from years to decades, and not event responses, are appropriate.

Wilson (1977) analysed monthly sediment discharges from 100 drainage basins together with data from 1400 other catchment areas. Olivry (1977) measured sediment load using ORSTOM methodology, and assessed SY (28-210 ton.km^{-2}.a^{-1}) for three large watersheds (up to 77,000 km^2) in Cameroon. Ichim (1990) estimated SY and the corresponding SDR in three Romanian basins measuring sediment load, and concluded that SDR held an inverse relationship with the Strahler drainage basin order. Yu & Neil (1994) studied temporal and spatial variations of SY (2.4-23 ton.km^{-2}.a^{-1}) in a mountainous watershed in Australia using sediment load approach for data from 20 gauging stations.

Higgitt & Lu (2001) analysed 30 years of runoff and SY (524 ton.km^{-2}.a^{-1}) data for 250 gauging stations in the Upper Yangtze River basin (1 million km^2), upstream the Three Gorges Project, acquiring information for management analysis. Gangyan & Zhian (1994) studied the whole Yangtze River basin (1.8 million km^2) using 40 years of sediment load data, concluding that SDR is smaller for whole basin (262 ton.km^{-2}.a^{-1}) due to the suspended-sediment concentration decreasing downstream of Yichang.

Costa (1994) evaluated the evolution of SY after the eruption of Mount St. Helen, USA, in May 1980. Five sites were monitored daily in terms of discharge and suspended-sediment concentration. Kuhnle et al. (1996) assessed the effect of land use change on sediment production through measurements in two nested basins (17.9 and 21.3 km^2). Agricultural land decrease led to SY reduction: erosion change caused fine sediment reduction, whilst runoff change caused sand and gravel reduction.

The regular hydro-sedimentometric practice in water-scarce Bulgaria is suspended-sediment concentration sampling, but Gergov (1996) proposed the use of remote sensing (by correlation of sediment concentration and spectral characteristics of the image) to enhance temporal and spatial resolution. Carvalho & Cunha (1998) presented a complete review on sediment load data from the Amazon River, whereas Krishnaswamy et al. (2000) analysed 40 years (1951-1990) of SY data in the Yadkin River basin (5,905 km^2, USA) to investigate effects of reforestation, urbanization and high-intensity events on SY. Carvalho et al. (2000) studied the sedimentation of a small reservoir to be built in Brazil, using suspended-sediment data (1979-1982) and modified Einstein Method for bedload estimation, and suggested reservoir service life of only 12 years. Gergov & Karagiozova (2002) presented SY data for 13 Bulgarian rivers (1961-2000), with an average of 125 ton.km^{-2}.a^{-1}. Figueiredo & Bathurst (2002) used six to ten-year measurements in the representative basin of Sumé (see Srinivasan & Galvão, 2003), in various scales, to assess runoff and SY in semiarid Brazil. Yabe (2003) used Brown bedload formula and 60-year sediment-load data from Japan to correlate SY and forest cover in a weathered granite mountain area. McKergow et al. (2003) addressed the question of riparian vegetation and its capacity to retain sediment and nutrients. Machado & Vettorazzi (2003) monitored SY (average 422 ton.km^{-2}.a^{-1}) in an experimental Brazilian basin (59.7 km^2), and associated it with satellite images and daily climate and hydro-sedimentological data.

River morphologic surveys may also add to the sediment load technique.

Kasai et al. (2001) estimated SDR in the Waipaoa River basin, New Zealand, by monitoring morphologic changes in river sections over 28 years, showing that gullies were shrinking due to reforestation started in the 1960s. Likewise, Abril & Knight (2004) monitored the morphology of the Paute River, Ecuador, while proposing a master plan to stabilise it.

Another frequently used technique to assess medium-term SY in watersheds is the temporal morphological survey of reservoirs (Morris & Fan, 1997). The measurement of the dry bulk density (dBD) of the deposited sediments (accomplished by core samples) allows computation of sediment mass trapped in the reservoir. If trap efficiency is known, SY can then be inferred. Verstraeten & Poesen investigated the sensitivity of dBD (2001a) and trap efficiency (2001b) on SY estimation after studying 13 retention ponds in Belgium. Measurements showed variation of dBD (0.78-1.35 $ton.m^{-3}$) and trap efficiency (58%-96%), and errors up to 72% in SY estimation were obtained for inadequate dBD and trap efficiency estimation. Zarris et al. (2002) also recommended reservoir surveying as a "realistic and reliable alternative method for sediment yield investigation", and applied it to the Acheloos River basin, Greece, controlled by a 3-billion m^3 reservoir.

Lal et al. (1977) observed the scarcity of medium-term SY data for large basins and developed a programme to survey reservoirs in India. Wasson (1994) used not only suspended-sediment data, but also reservoir sedimentation surveys to assess medium-term SY (12-1,830 $ton.km^{-2}.a^{-1}$) in Australia. Takahashi & Nakagawa (1997) also used the reservoir-sedimentation approach to analyse SY in Japan. In order to perform meso-scale analysis of SY, Hinderer & Schäuble (2003) used both suspended-sediment data (700 stations) and sediment trapping dams data (1500 units). Wright & Schoellhamer (2003) used river sediment load and reservoir sedimentation techniques to assess SY showing a temporally decreasing trend, possibly due to riverbank protection and trapping of sediment in upstream reservoirs. Nichols & Renard (2003) studied up to 46 years of data from the Walnut Gulch experimental watershed using 'stock tanks' to measure SY in semiarid basins (0.35-0.92 km^2), finding average SY 220 $ton.km^{-2}.a^{-1}$ and high temporal variation. Araújo (2003) monitored reservoir sedimentation and corresponding SY (average 426 $ton.km^{-2}.a^{-1}$) in seven watersheds (3-1,221 km^2 and 45-95 years sedimentation history) in Brazilian semiarid region.

What concerns urban watersheds, Araújo et al. (2003) estimated per-capita urban contribution of S.Jorge watershed in Brazil, as 0.6 $kg.a^{-1}$. Soares (2003) studied historical land use of S.Anastacio urban watershed, Brazil; comparing reservoir morphology in 2002, 1992 and 1918; and collecting core samples for x-ray analysis. The average per-capita contribution was 21 $kg.a^{-1}$. The higher sediment contribution of the second watershed was mainly due to its lower sanitation level. Likewise, Nelson & Booth (2002) analysed a rapidly urbanizing 144-km^2 watershed (USA), where a 50% increase in sediment production was noticed. The authors estimated present-day SY as 44 $ton.km^{-2}.a^{-1}$, caused mainly by landslides (50%), channel-bank erosion (20%) and road erosion (15%). Krishnaswamy et al. (2000) also related increase in urban areas and road construction to rising trend of SY.

Some publications refer to combined techniques of reservoir sedimentation and radionuclides dating to achieve better resolution of temporal evolution of sedimentation. Walling et al. (1999) used Caesium 137 (^{137}Cs) to estimate SY (480 $ton.km^{-2}.a^{-1}$) for medium-term periods (from 1950s-1960s due to bomb-test activities, see also Cisternas et al., 2001) and Beryllium 7 (^{7}Be) for shorter periods. Lu & Higgit (2001) estimated SY of 3,500 $ton.km^{-2}.a^{-1}$ in a small reservoir catchment in China, compatible with SY obtained by sedimentation survey of 38 reservoirs (deposition history of at least 15 years) in the Sichuan basin. They also used ^{137}Cs to investigate temporal SY evolution. Gellis et al. (2002) estimated SY using sediment traps and straw dams from 1996 to 1998 in a 2.3-km^2 semiarid basin, USA. They compared the results of medium-term yield (200–1,800 $ton.km^{-2}.a^{-1}$) with those of long-term yield (270 $ton.km^{-2}.a^{-1}$), obtained by radionuclide ^{10}Be dating technique.

5. Long-term response measurement

Walling & He (1994) relied on ^{210}Pb measurements to assess overbank depositions in British rivers throughout time, and devised median sedimentation rates of 3,000 $ton.km^{-2}.a^{-1}$ for the last 100 years, which was similar to the 35-year value (with ^{137}Cs). Likewise, Cisternas et al. (2001) used ^{210}Pb and ^{137}Cs dating to infer effect of historical land use on SY in a 4.5-km^2 Chilean watershed. Results of a core sample analysis from San Pedro Lake (formed by sediment blocking of a ravine after the last glaciation) showed inorganic SY of 50 $ton.km^{-2}.a^{-1}$ in the late 1800s and 600 $ton.km^{-2}.a^{-1}$ in the late 1960s. De Boer (1994) analysed recent geological erosion in Canada, separating pre and post European settlement sedimentation based on Populus pollen, indicating temporal increase in erosion. Schiefer et al. (2001) studied 70 lake catchments (0.9-190 km^2) in the Canadian Cordillera using ^{210}Pb, confirming the impact of changing land-use on sedimentation over the last 150 years. Lamoureux (2000) assessed long-term SY variation in Canada (Nunavut) through piston-percussion and vibracoring techniques. The analysis of 487 years of SY led to the conclusion that extreme events occurred most frequently in the 17th and 19th centuries. Owens & Slaymaker (1994) researched the temporal variability of SY throughout the whole Holocene Epoch in Canada, with average SY below 5 $ton.km^{-2}.a^{-1}$, increasing with time. Gellis et al. (2002) relied on ^{10}Be data to estimate SY at the time scale up to 20,000 years in USA. Heimsath et al. (2001) presented a study concerning soil production and erosion rates using the cosmogenic radionuclide accumulation methodology through analysis of ^{10}Be and ^{26}Al. Results showed maximum soil production rate 268 m.Ma^{-1}, erosion rate 117 m.Ma^{-1}, and "evidence for the stochastic and large-scale nature of the soil production and transport processes" (p. 549).

6. Data analysis

Figure 1a shows the relationship, according to this review, between four SY-measurement methodologies and the respective temporal scales: micro-morphology (12 hours - 2 years); sediment load (1 day - 60 years); river/reservoir topographic survey (1-130 years); and radionuclides (15-20,000 years). It is noticeable that the SY measurement techniques have a direct relationship with the temporal scale, and that the sediment load technique has the broadest applicability (10^{-3}-10^{2}yr).

Walling (1983) presented curves from several researches relating SY and catchment area, showing that usually SY declines as catchment area increases. Church & Slaymaker (1989), nonetheless, using data from British Columbia watersheds, Canada, observed a consistent pattern of increasing SY with the area (positive allometry) up to $3x10^4$ km^2. The authors concluded that, for areas above 1 km^2, SY was a consequence of the glacial events of the Quaternary Period. Based on a large and consistent database for SY in Australia, Wasson (1994) observed that, except for the Ord river basin, which presented positive allometry, SY decreases with increase of basin area. Wasson stated that the Australian data "add to the argument of Church & Slaymaker" (p. 278). Lane et al. (1997) analysed data from USA (Dendy & Bolton, 1976) and Australia (Wasson, 1994) and affirmed that SY "should be strongly influenced by, but not completely determined by, watershed area" (p.356, see also Lane & Hermandez, 1997). Higgitt & Lu (2001) presented a regression equation in which SY decreases with increasing drainage area upstream the Three Gorges Project. Schiefer et al. (2001) investigated 70 lakes in the Canadian Cordillera and concluded that "the positive allometry (...) for the Coast Mountains fits the Church and Slaymaker model" (p.63), whilst negative allometry was observed in plateau areas, concluding that SY-area models are only appropriately applied to the region for which they were generated. Gellis et al. (2002) affirmed that the SY data for the Arroyo Chaves semiarid watershed, USA, presented no trend concerning the watershed area, contrasting the general negative allometry observation (e.g. Walling, 1983).

Figure 1b, contrasting Figure 1a, shows little correlation between SY measurement methodology and applicable catchment area, except for the micro-morphology approach, which has not been used for areas over 200 m^2.

This review paper compiles SY mean annual data of 364 catchments in 33 countries ranging from less than 1ha to over 6 million km^2. The sources are the individual publications referred to in the manuscript, as well as several works of the IAHS Proceedings edited by Bordas & Walling (1988). The SY data presented no global trend concerning a possible positive or negative allometry

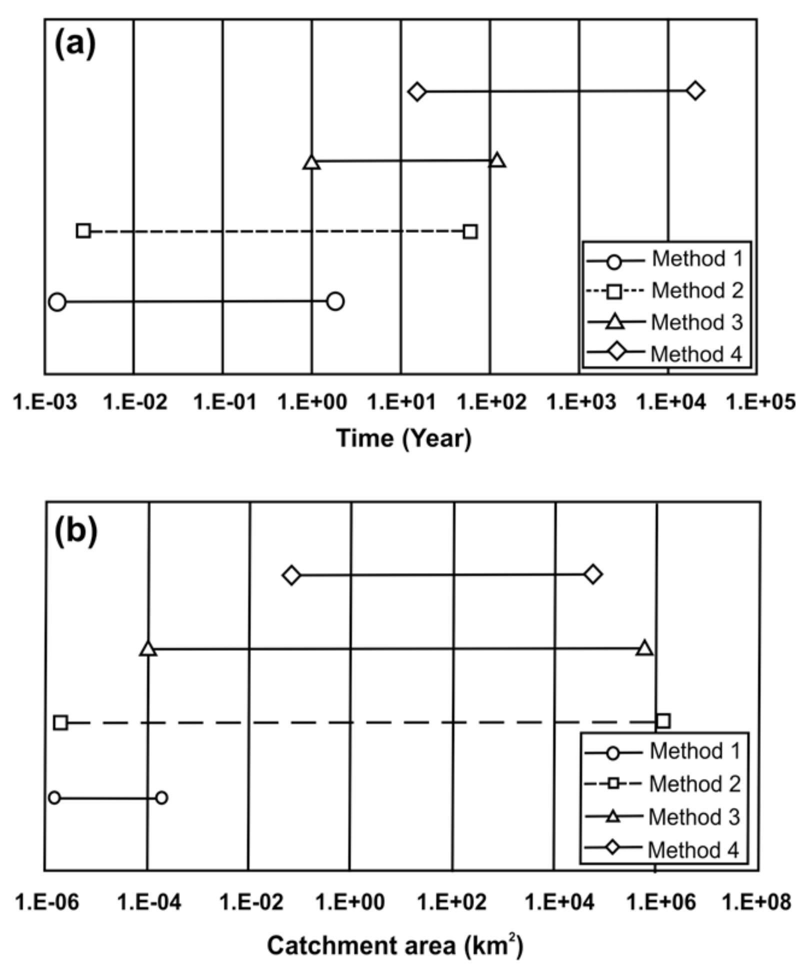

Figure 1 - Temporal (a) and spatial (b) applicability of four SY measurement methods according to selected literature (Method 1: micro-morphology; Method 2: sediment load; Method 3: river/reservoir topographic survey; Method 4: radionuclides).

(see Figure 2). The African data, however, showed consistent decrease of SY with increasing area (r^2 = 0.647). Table 1 presents SY average, standard deviation, median, minimum and maximum values for the Continents and Figure 3 presents SY median values of the available data for eleven countries.

7. Conclusions

The present paper collected and briefly discussed the state-of-the-art papers concerning measurements of sediment yield (SY). There was often reference to the lack of reliable, long-term SY data, and the establishment of a SY database for larger areas was proposed. It was observed that the SY measurement methodologies bear a much closer relationship to the temporal than to the spatial resolution (Figure 1). Data from 364 watersheds ranged from 0.005 to 6,400 ton.km^{-2}.a^{-1} with global median 190 ton.km^{-2}.a^{-1}. No global SY trend concerning catchment area (Figure 2) was found, although African data presented negative allometry (Figure 2).

8. Acknowledgement

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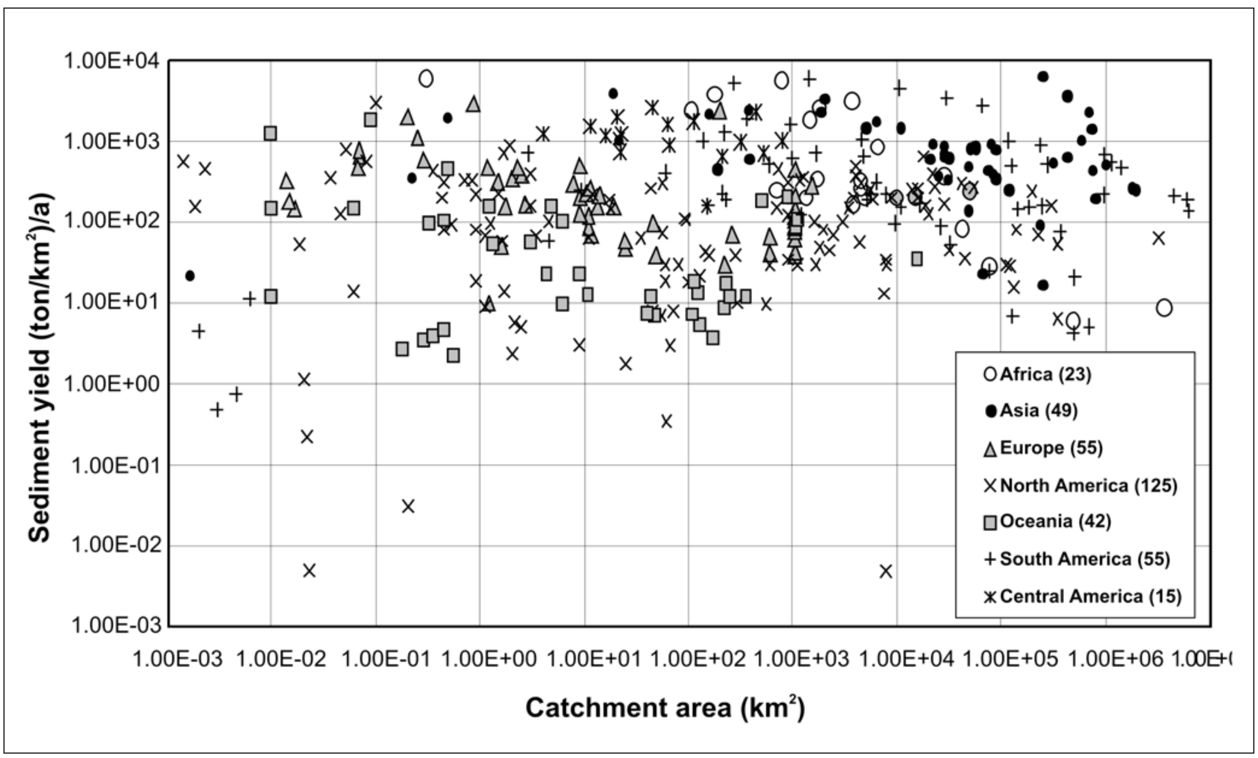

Figure 2 - Average annual sediment yield versus catchment area (364 catchments, 33 Countries). The numbers in parenthesis in the legend refer to the number of catchments.

Table 1 - Measured sediment yield (ton.km^{-2}.a^{-1}) in several locations extracted from selected literature.

Location	Number of watersheds (countries)	Global average SY	Coefficient of variation SY	Global median SY	Minimum catchment SY	Maximum catchment SY	Watershed minimum SY	Watershed maximum SY
Africa	23 (4)	1304	1.44	260	6	6150	Oubanqui, Congo	Kapthurin, Kenya
Asia	49 (8)	1153	1.10	663	16	6400	Krishna, India	Yellow R., China
Central America	15 (2)	1380	0.44	1227	659	2651	Caonillas, Puerto Rico	Luchetti, Puerto Rico
Europe	55 (8)	366	1.57	160	10	2883	Glonn, Germany	Laval, France
North America	125 (2)	219	1.84	99	0.005	3000	Galie, Canada	Coon Creek, USA
Oceania	42 (2)	138	2.45	21	2	1830	Bald Hill 3, Australia	S. Uplands, Australia
South America	55 (7)	752	1.71	221	1	6000	R. Grande, Argentina	Tamampaya, Bolivia
Global	364 (33)	554	1.79	190	0.005	6400	Galie, Canada	Yellow R., China

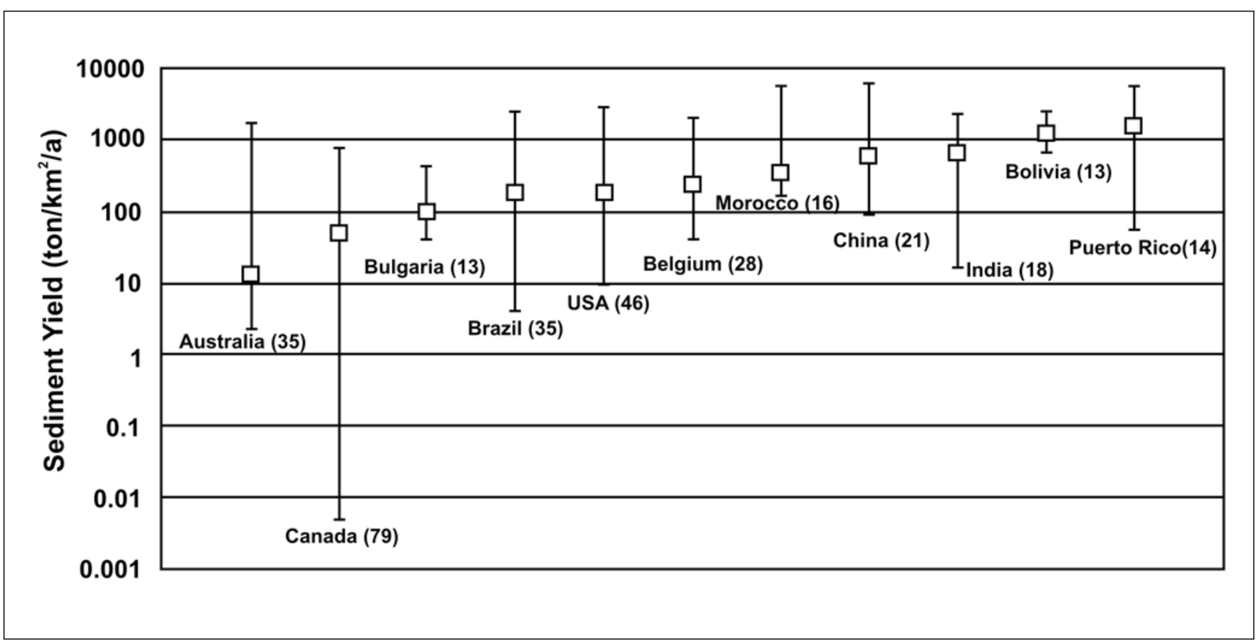

Figure 3 - Median, maximum and minimum sediment yield of the available data for several countries. The number of catchments is shown in parenthesis.

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