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Sediment yield in Africa

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ABSTRACT

Several studies have compiled and analysed measured contemporary catchment sediment yield (SY, [t km^{-2} y^{-1}]) values for various regions of the world. Although this has significantly contributed to our understanding of SY, Africa remains severely underrepresented in these studies. The objective of this article is therefore: (1) to review and compile available SY data for Africa; (2) to explore the spatial variability of these SY data; and (3) to examine which environmental factors explain this spatial variability.

A literature review resulted in a dataset of SY measurements for 682 African catchments from 84 publications and reports, representing more than 8340 catchment-years of observations. These catchments span eight orders of magnitude in size and are relatively well spread across the continent. A description of this dataset and comparison with other SY datasets in terms of spatial and temporal distribution and measurement quality is provided. SY values vary between 0.2 and 15,699 t km^{-2} y^{-1} (median: 160 t km^{-2} y^{-1}, average: 634 t km^{-2} y^{-1}). The highest SY values occur in the Atlas region with SY values frequently exceeding 1000 t km^{-2} y^{-1}. Also the Rift region is generally characterised by relatively high SY values, while rivers in Western and Central Africa have generally low SY values.

Spatial variation in SY at the continental scale is mainly explained by differences in seismic activity, topography, vegetation cover and annual runoff depth. Other factors such as lithology, catchment area or reservoir impacts showed less clear correlations. The results of these analyses are discussed and compared with findings from other studies. Based on our results, we propose a simple regression model to simulate SY in Africa. Although this model has a relatively low predictive accuracy (40%), it simulates the overall patterns of the observed SY values well. Potential explanations for the unexplained variance are discussed and suggestions for further research that may contribute to a better understanding of SY in Africa are made.

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1. Introduction

Understanding the factors and processes controlling contemporary catchment sediment yield (SY, [t km^{-2} y^{-1}]; i.e. the mass of sediment annually leaving a catchment per unit of catchment area) is crucial for our comprehension of global denudation rates, biogeochemical cycles, fluvial sedimentary archives and human impacts on sediment fluxes (e.g. Meybeck, 2003; Walling, 2006; Syvitski and Milliman, 2007). Several studies therefore compiled and analysed worldwide SY observations (e.g. Jansen and Painter, 1974; Walling and Kleo, 1979; Dedkov and Mozzherin, 1984; Jansson, 1988; Milliman et al., 1995; FAO, 2008; Milliman and Farnsworth, 2011). Despite its size and physiographic variability (Goudie et al., 1996), Africa is clearly underrepresented in these compilations (Table 1). So far, the FAO (2008) conducted the largest SY data compilation for Africa (Table 1). However, almost half of the 205 African SY observations in this dataset are located in Algeria, Morocco or Lesotho while most other African countries are not or poorly represented (FAO, 2008). Moreover, the few African SY data included in these compilations are mainly for larger river systems (>10,000 km^2). Smaller catchments (<100 km^2) are even more underrepresented (Table 1).

The main reason for this under representation is the limited number of African SY observations available. This was already highlighted by Walling (1984). Nonetheless, a large number of SY measurements have been conducted in Africa but were often only published in internal reports, theses, conference proceedings or local research journals. This is illustrated by a few regional or country-wide SY compilations in Africa (e.g. Rooseboom, 1978; Dunne, 1979; Nyssen et al., 2004; Liénou et al., 2005; Balthazar et al., 2012). Whereas these compilation studies are an important step forward, a comprehensive continent-wide compilation of African SY data is currently lacking. As a result, our insight into the spatial patterns of SY in Africa is limited (e.g. Walling and Webb, 1983; Walling, 1984; Milliman and Farnsworth, 2011).

Also our ability to predict SY of African rivers is hampered by this lack of data. Some models have been proposed to predict SY for specific African regions, but they are mostly based on a relatively limited number of catchments and involve large uncertainties when applied to catchments in other regions (e.g. Picouet et al., 2001; Ning Ma, 2006; Haregeweyn et al., 2008; Meshesha et al., 2011; Schmengler, 2011; Balthazar et al., 2012). Furthermore, these studies focus on only a few specific African regions (e.g. the Ethiopian Highlands; Haregeweyn et al., 2008; Meshesha et al., 2011; Balthazar et al., 2012). Also earlier developed SY models remain poorly tested for African conditions, while studies aiming to apply existing SY models to African catchments often report poor model performances and/or high data requirements (e.g. Bouraoui et al., 2005; Syvitski and Milliman, 2007; Balthazar et al., 2012; Bossa et al., 2012; Pelletier, 2012; de Vente et al., 2013).

It is generally accepted that SY is influenced by catchment area, lithology, topography, land cover, reservoir impacts and climatic conditions (e.g. de Vente and Poesen, 2005; Syvitski and Milliman, 2007; Pelletier, 2012). However, the relative importance of these factors in explaining spatial variation in SY is not fully understood as this also depends on the catchments considered. This issue has been raised before and is evident from the fact that different studies often report different factors controlling SY (e.g. Jansen and Painter, 1974; Walling, 1983; Lane et al., 1997; de Vente et al., 2005, 2006; Syvitski and Milliman, 2007; Haregeweyn et al., 2008; de Vente et al., 2013). Most studies dealing with factors controlling SY focus either on large river basins worldwide (e.g. Syvitski and Milliman, 2007; Pelletier, 2012) or on smaller catchments in a specific region (e.g. Dunne, 1979; Liénou et al., 2005; Haregeweyn et al., 2008). Very few studies consider a wide range of catchment sizes or regional differences at a continental scale.

Furthermore, tectonic activity is generally not considered as a potential controlling factor of SY (e.g. Milliman and Syvitski, 1992; de Vente and Poesen, 2005; Syvitski and Milliman, 2007; Pelletier, 2012; de Vente et al., 2013) with the exception of some studies in highly tectonically active regions (e.g. Dadson et al., 2003; Hovius et al., 2011). Mostly, it is implicitly assumed that the effects of tectonic activity are either irrelevant or reflected in the catchment topography (e.g. Syvitski and Milliman, 2007). However, recent studies indicate that this is not always the case: spatial variation in soil erosion rates and SY can partly be attributed to spatial differences in seismic activity, even in regions where this activity is relatively limited (e.g. Cox et al., 2010; Portenga and Bierman, 2011; Vanmaercke et al., 2014a,b). Nonetheless, the importance of seismic activity as an explaining factor of SY remains poorly understood. The large variation in land cover and climatic

Table 1
Overview of global sediment yield (SY) inventories, their total number of catchments for which SY was observed, the number of SY observations in Africa, the relative share of SY observations that was measured in Africa and the range of catchment areas (A) for the included African SY observations. 'N.A.' means not available.

Reference	Total # SY-observations	# African SY-observations	% of African observations	A-range Africa (km^2)
Holeman (1968)	110	5	4.5	2.1×10^4–4.0×10^6
Fournier (1969)	139	0	0.0	N.A.
Jansen and Painter (1974)	79	3	3.8	1.1×10^6–4.0×10^6
Walling and Kleo (1979)	1246	13	1.0	N.A.
Dedkov and Mozzherin (1984)	3763	45	1.2	1.9×10^1–3.7×10^6
Jansson (1988)	1358	117	8.6	>300[a]
de Araújo and Knight (2005)	364	23	6.3	2.9×10^{-1}–3.6×10^6
Meybeck and Ragu (1995)	219	24	11.0	9.0×10^3–3.6×10^6
Milliman et al. (1995)	401	43	10.7	3.0×10^2–3.8×10^6
FAO (2008)	869	205	23.6	1.9×10^1–4.0×10^6
Milliman and Farnsworth (2011)	776	66	8.5	1.8×10^1–3.8×10^6

[a] 300 km^2 is the minimum A for the global dataset. The A-range for African catchments could not be retrieved.

conditions in combination with the overall low degree of seismic activity (e.g. Shedlock et al., 2000; ANSS, 2013) makes the African continent an interesting case to further investigate the potential role of seismic activity as a controlling factor of SY.

However, understanding the factors controlling SY in Africa is not only of interest from a merely scientific point of view. The rapidly growing population (UN-ESA, 2011) and the projected climate changes (e.g. de Wit and Stankiewicz, 2006) will result in a larger need for dams and reservoirs to respond to the increasing energy and water demands in Africa (e.g. Bartle, 2002; Karekezi and Kithyoma, 2002; Alhassan, 2009; Vanmaercke et al., 2011a; Wisser et al., 2013). Moreover, population growth and climatic changes have important impacts on the land cover of various African regions (e.g. Barnes, 1990; Nyssen et al., 2004; Zhang et al., 2006; Odada et al., 2009). These changes often pose significant threats to the sustainable use of available water resources (e.g. Ogutu-Ohwayo et al., 1997; Lewis, 2000; Bruijnzeel, 2004; Nyssen et al., 2004; Odada et al., 2004; Reichenstein et al., 2013). For example, numerous constructed or planned water reservoirs in Africa face important capacity losses due to high siltation rates (e.g. Kabell, 1984; Liebe et al., 2005; Haregeweyn et al., 2006; Adwubi et al., 2009; Amegashie et al., 2011; Baade et al., 2012). Also many of the Great African Lakes face important ecological problems, related to the input of sediments and sediment-fixed nutrients (e.g. Ogutu-Ohwayo et al., 1997; Odada et al., 2004). Reliable information on the expected SY and its sensitivity to land cover or climate changes is therefore crucial for sustainable catchment management and water harvesting projects. However, the lack of SY measurements and our inability to make reliable predictions often impede the design of such projects (e.g. Haregeweyn et al., 2006).

A continent-wide compilation and analysis of SY measurements in Africa could strongly improve our understanding of the factors controlling SY and help addressing these challenges. The objectives of this study are therefore: (1) to present and discuss a compilation of measured SY data in Africa, based on an extensive literature review (Section 2); (2) to explore the spatial variability of SY (Section 3); and (3) to examine which factors best explain the variability in observed SY (Section 4).

2. A database of African sediment yield observations

2.1. Data collection and quality assessment

Based on an extensive literature review of scientific publications, conference proceedings, MSc. and PhD. theses and reports from hydrological and environmental institutes, a database was constructed with measured catchment SY data for African rivers. Only SY data that were derived from measurements at a gauging station or from reservoir siltation rates over a measuring period of at least one year were considered. Each entry in the database corresponds to one catchment for which SY has been measured and contains the original source of the data, the catchment and/or location name, the location of the catchment outlet, the measured SY value, the type of measurement (observation at a gauging station ('GS') or derived from a reservoir sedimentation rate ('R')), the originally reported catchment area, and if available the measuring period. For several entries, the measuring period was not reported but known to be longer than one year. In these cases, the measuring period was indicated as unknown. If available, the coordinates of the catchment outlets were based on the originally reported coordinates. If not, an assessment was made based on information provided in the publication and Google™ Earth. SY observations for which the measuring location could not be estimated were not included in the database.

The compiled SY data was measured and calculated using various techniques and procedures. This has important implications for the analyses of these data. Especially the difference between SY values derived from reservoir siltation and those obtained from gauging station measurements impedes the comparability of SY observations. Earlier studies have shown that SY-estimates based on low-frequency sampling (e.g. Phillips et al., 1999; Moatar et al., 2006) or short (<5 yr) measuring periods (Vanmaercke et al., 2012) are more likely to underestimate the true sediment yield because they have a higher probability of excluding low-frequency but high-magnitude events. Especially short-term SY values derived from gauging station measurements are susceptible to such underestimations, while SY estimates based on long-term sedimentation rates in reservoirs with high trapping efficiencies often provide more reliable estimates of the average SY (Verstraeten and Poesen, 2002). Moreover, SY estimates derived from reservoir sedimentation rates include both suspended and bedload, while almost all SY values measured at gauging stations only consider the suspended load. It is therefore likely that observed differences in SY can, for an important part, be attributed to methodological differences.

To account for this, we explicitly considered this difference in measuring method (GS or R) in our analyses. In addition, we assessed the reliability of each SY observation. Based on the (often limited) available information about the applied measuring procedure, the quality of each SY observation was labelled as 'good', 'acceptable', 'poor' or 'unknown'. GS entries classified as 'good' are typically observations for which runoff discharge and sediment concentrations (SC) were measured at least daily (e.g. Walling et al., 2001). 'Acceptable' entries mainly consist of SY values based on daily runoff measurements while SC was measured at least weekly. Also SY observations for which SC values were estimated based on rating curves with at least 50 observations are included in this category (e.g. Carré, 1972). GS-entries based on a lower sampling frequency or based on rating curves with less than 50 observations were classified as having a 'poor' data quality (e.g. Sichingabula, 2000). SY estimates based on sediment deposition rates in reservoirs with a high estimated trapping efficiency (>90%) for which the sediment dry bulk density was measured and for which a correction for the trapping efficiency was applied were classified as having a 'good' data quality (e.g. Haregeweyn et al., 2012). Trapping efficiency values were estimated using an empirical equation proposed by Brown (1943). SY estimates derived from sedimentation rates in reservoirs with a high trapping efficiency that were corrected for trapping efficiency but for which the dry bulk density was not measured were classified as 'acceptable' (e.g. Rooseboom et al., 1992). R-entries that did not meet these criteria or for which it was suspected that the estimated annual sedimentation volume was susceptible to considerable uncertainties were classified as having a 'poor' data quality (e.g. Ndomba, 2011). For 245 entries, no or insufficient information on the measuring method could be found in their source to allow a quality assessment. These entries were labelled as having an unknown data quality (e.g. Milliman and Farnsworth, 2011).

Evidently, also these quality assessments are subject to uncertainties, since also other sources of error can affect the reliability of the SY observations. Nonetheless, earlier studies clearly indicate that the reliability of sediment yield estimates based on measurements at gauging stations is mainly determined by the sediment concentration sampling frequency and/or the number of sediment concentration samples used to establish rating curves (e.g. Phillips et al., 1999; Moatar et al., 2006; Vanmaercke et al., 2010; Delmas et al., 2011). Likewise, the reliability of SY estimates based on reservoir sedimentation rates strongly depends on the trapping efficiency and the (often estimated) dry bulk density of the sediments (e.g. Verstraeten and Poesen, 2002). The criteria used in this study can therefore be expected to consider the most important sources of uncertainty on SY-measurements.

For many catchments multiple alternative SY estimates exist. Therefore, the database was thoroughly checked for duplicate entries. Two entries were considered as duplicates if they had the same outlet and (hence) the same catchment area. In such case only the SY measurement that was deemed to be the most reliable was selected. When the estimated quality of both entries was equal or unknown, the entry with the longest measuring period was selected. This was done because average SY values based on a short (<5 years) measuring period may be susceptible to large (>100%) uncertainties (e.g. Olive and Rieger, 1992; Vanmaercke et al., 2012). If also the measuring periods were equal or unknown, the source that provided the most detailed information on the catchment outlet and measuring technique was selected.

2.2. Data availability

An overview of all collected sediment yield data per country and the original sources of the data is given in Table 2. In total SY data for 682 catchments in Africa were collected. For 377 of these catchments, SY was measured at gauging stations. For the other 305 catchments, SY

Table 2
Overview of all collected sediment yield (SY) data. For each country, the number of catchments (#), the corresponding number of catchment-years (catch. yr), the minimum and maximum catchment areas (A) of the entries, the minimum and maximum reported SY values, and the sources of the data are indicated. For the number of catchments and catchment-years, a distinction is made between SY data derived from gauging station measurements (GS) or from reservoir sedimentation rates (R). 'N.A.' indicates that no data are available.

Country	# GS (catch. yr)	# R (catch. yr)	Total # (catch. yr)	Min A–max A (km^2)	Min SY–max SY (t km^{-2} y^{-1})	Sources
Algeria	45 (307)	32 (836)	77 (1143)	93–44,000	63–7273	Achite and Ouillon (2007), Bengueddach and Chabouni (1997), FAO (2008), Ghenim et al. (2008), Hooke (2006), Khanchoul et al. (2009), Lahlou (1996), Milliman and Farnsworth (2011), Terfous et al. (2003), Touaibia (2010)
Benin	1 (1)	N.A.	1 (1)	50,000–50,000	48–48	Milliman and Farnsworth (2011)
Botswana	1 (1)	N.A.	1 (1)	530,000–530,000	0.4–0.4	McCarthy and Metcalfe (1990)
Burkina Faso	N.A.	3 (39)	3 (39)	7.9–24	30–441	Schmengler (2011)
Cameroon	20 (60)	1 (1)	21 (61)	0.58–130,000	2.9–330	Dedkov and Mozzherin (1984), Liénou et al. (2005), Liénou (2007), Liénou et al. (2009), Milliman and Farnsworth (2011)v Ndam Ngoupayou et al. (2007), Nouvelot (1969), Olivry (1977)
Cape Verde	5 (30)	N.A.	5 (30)	1.9–11	10–4300	Olivry et al. (1989), Tavares (2010)
Central African Rep.	7 (14)	N.A.	7 (14)	2590–553,900	3.1–9.3	Coynel et al. (2005), Laraque et al. (2009), Liénou et al. (2005), Walling (1984)
Chad	10 (31)	N.A.	10 (31)	14,300–515,000	1.2–65	Carré (1972), Dedkov and Mozzherin (1984), Liénou et al. (2005)
Congo D.R.	7 (11)	N.A.	7 (11)	8.5–3,800,000	2.4–70.6	Bombi et al. (2000), Laraque et al. (2009), Lootens and Kishimbi (1986), Lootens and Lumbu (1986), Milliman and Farnsworth (2011)
Congo Republic	6 (18)	N.A.	6 (18)	13,500–3,500,000	4.2–9.4	Laraque et al. (2009), Liénou et al. (2005)
Egypt	N.A.	1 (1)	1 (1)	2,960,000–2,960,000	41–41	Shahin (1993)
Eritrea	N.A.	1 (17)	1 (17)	174–174	2241–2241	Nyssen et al. (2004)
Ethiopia	58 (323)	20 (124)	78 (447)	0.72–172,254	0.2–8387	Balthazar et al. (2012), BCEOM (1997), FAO (2008), Guzman et al. (2012), Haregeweyn et al. (2008), Haregeweyn et al. (2012), Kissi et al. (2011), Meshesha et al. (2011), Nyssen et al. (2004), Nyssen et al. (2009), SCRP (2000a, 2000b, 2000c, 2000d, 2000e), Shahin (1993), Tamene et al. (2006), Vanmaercke et al. (2010), Van Opstal (2011), Zenebe et al. (2013)
Gambia	1 (1)	N.A.	1 (1)	77,000–77,000	2.6–2.6	Milliman and Farnsworth (2011)
Ghana	21 (33)	5 (50)	26 (83)	0.35–400,000	9.1–15,699	Adwubi et al. (2009), Akrasi (2005), Akrasi and Ansa-Asare (2008), Amegashie et al. (2011), Milliman and Farnsworth (2011)
Guinea	2 (2)	N.A.	2 (2)	9600–16,000	21–24	Liénou et al. (2005), Milliman and Farnsworth (2011)
Ivory Coast	7 (10)	N.A.	7 (10)	0.02–97,000	6.1–169	Mathieu (1971), Milliman and Farnsworth (2011)
Kenya	20 (161)	4 (26)	24 (187)	24–42,000	8.2–6330	Brown et al. (1996), FAO (2008), Kithiia, (1997) Milliman and Farnsworth (2011), Ning Ma (2006), Ongweny (1978), Ongwenyi et al. (1993), UN-WATER (2006)
Lesotho	16 (98)	N.A.	16 (98)	212–19,875	3–2050	FAO (2008)
Liberia	1 (1)	N.A.	1 (1)	28,000–28,000	189–189	Milliman and Farnsworth (2011)
Madagascar	6 (9)	N.A.	6 (9)	575–59,000	169–3130	FAO (2008), Milliman and Farnsworth (2011)
Malawi	17 (19)	N.A.	17 (19)	0.05–12,110	7.2–1605	Amphlett (1984), Hecky et al. (2003)
Mali	8 (37)	N.A.	8 (37)	17.5–141,000	3.9–31	Droux et al. (2003), Liénou et al. (2005), Picouet (1999), Picouet et al. (2001)
Morocco	19 (19)	19 (314)	38 (333)	7.66–114,000	100–4620	Abdellaoui et al. (2002), FAO (2008), Hooke (2006), Jansson (1982), Milliman and Farnsworth (2011), Walling (1984)
Mozambique	2 (2)	1 (1)	3 (3)	410,000–1,300,000	37–135	Bolton (1984), Milliman and Farnsworth (2011)
Niger	10 (29)	N.A.	10 (29)	7500–757,640	4.8–25	Amogu (2009), Gallaire (1986)
Nigeria	13 (35)	N.A.	13 (35)	2653–2,200,000	7–344	Dedkov and Mozzherin (1984), FAO (2008), Milliman and Farnsworth (2011)
Senegal	5 (16)	N.A.	5 (16)	7500–270,000	2.1–11	Liénou et al. (2005), Milliman and Farnsworth (2011)
South Africa	38 (333)	136 (4318)	174 (4651)	0.18–1,000,000	1–890	Baade et al. (2012), Dedkov and Mozzherin (1984), FAO (2008), Foster et al. (2012), Milliman and Farnsworth (2011), Rooseboom (1978), Rooseboom et al. (1992), Scott et al. (1998)
Sudan	9 (71)	1 (13)	10 (84)	16,000–2,600,000	38–3422	Billi and el Badri Ali (2010), Dedkov and Mozzherin (1984), FAO (2008), Nyssen et al. (2004)
Tanzania	6 (24)	11 (221)	17 (245)	1.2–180,000	3.8–3132	Dedkov and Mozzherin (1984), FAO (2008), Milliman and Farnsworth (2011), Ndomba (2011), Nkotagu and Mbwano (2000), Rapp et al. (1972), Sichingabula (2000)
Togo	1 (1)	N.A.	1 (1)	29,000–29,000	55–55	Milliman and Farnsworth (2011)
Tunisia	2 (2)	41 (286)	43 (288)	0.85–22,000	149–5070	Boufaroua et al. (2006), Ghorbel and Claude (1977), Lahlou (1996), Milliman and Farnsworth (2011)
Uganda	8 (8)	N.A.	8 (8)	99–2121	23–164	Ryken (2011), Ryken et al. (2013)
Zambia	4 (6)	N.A.	4 (6)	54–686	1.2–21	Sichingabula (2000), Walling et al. (2001)
Zimbabwe	1 (1)	29 (379)	30 (380)	2.4–514,892	10–704	Bolton (1984), Dedkov and Mozzherin (1984), FAO (2008), Kabell (1984), Van den wall Bake (1986)
All data	377 (1714)	305 (6626)	682 (8340)	0.02–3,800,000	0.2–15,699	

was derived from reservoir sedimentation rates. Several African countries have no or only few SY data (Table 2). For some of these countries, more SY data most likely exists but could not be included because they were reported in documents that could not be retrieved (e.g. SY data for Kenya, reported by Dunne, 1979). The overview of SY data presented in this study therefore remains to some extent incomplete. Nevertheless, it is hitherto the largest SY compilation for Africa (Table 1).

Dividing the area of African continent by the number of SY measurements (682) results roughly in one SY observation per 44,300 km^2. This remains a relatively low density compared to other regions. A recent compilation of SY data using a similar approach as this study yielded SY measurements for 1794 catchments in Europe, corresponding to about one observation per 5700 km^2 (Vanmaercke et al., 2011b). Likewise, the USA has at least 1026 gauging stations where SY was monitored for at least one year (USGS, 2008) and 1823 reservoirs with sedimentation rate data available (Ackerman et al., 2009). Assuming that a SY value can be calculated for each of these reservoirs, this yields a total of ca. one SY observation per 3400 km^2.

Fig. 1 displays the outlet locations of all African catchments for which SY data were collected. This map illustrates clear regional differences in SY data availability. North-western, southern and large parts of eastern Africa are densely covered by SY observations, while no or only very few data are available for Central Africa and the Southwest of the continent. To a large extent, the lack of data in some regions can be easily explained by the presence of deserts (i.e. Sahara, Kalahari) or rainforest. Furthermore the availability of SY data (Fig. 1) closely corresponds to the availability of runoff discharge data (e.g. Hannah et al., 2011) and with the location of large dams and reservoirs in Africa (Lehner et al., 2011; Wisser et al., 2013). The spatial pattern shown in Fig. 1 therefore most likely reflects the true SY data availability in Africa.

2.3. Measuring periods, length of records and data quality

Assuming that SY values with an unknown measuring period are based on only one year of observations, the sum of all measuring periods for all compiled SY data yields a total of minimum 8340 catchment-years of observations (Table 2). A majority of the SY measurements at gauging stations have an unknown or relatively short (≤5 years) measuring period (Fig. 2). Excluding SY observations with an unknown measuring period, SY measurements at gauging station stations were on average conducted for 6.0 years (minimum: 1 year, median: 4 years, maximum: 54 years). This is considerably shorter than e.g. in Europe where SY at gauging stations was recorded for on average 13.2 years (Vanmaercke et al., 2011b). SY observations derived from reservoir sedimentation rates generally cover longer periods (Fig. 2; average: 24.8 years, minimum: 1 year, median: 17 years, maximum: 98 years).

Fig. 3 shows that SY measurements at gauging stations started around the 1930s but were mainly made between 1970 and 1990. After the 1990s, the number of GS observations dropped. The number of SY observations derived from reservoir sedimentation rates increases from the 1900s until the first half of the 1970s but then decreases over the next ten years. This sharp decrease can be partly attributed to two publications discussing reservoir sedimentation rates in South-Africa (Table 2; Rooseboom, 1978; Rooseboom et al., 1992). Nonetheless, the overall pattern of Fig. 3 illustrates a strong decrease in SY data availability after the 1990s. Similar trends were observed for SY data in Europe (Vanmaercke et al., 2011b), the number of reservoir sedimentation surveys in the USA (Ackerman et al., 2009) and the number of runoff discharge data worldwide (Vörösmarty, 2002; Hannah et al., 2011) and have been attributed to a worldwide decreased interest in hydrological measurements (e.g. Hannah et al., 2011; Vanmaercke et al., 2011b).

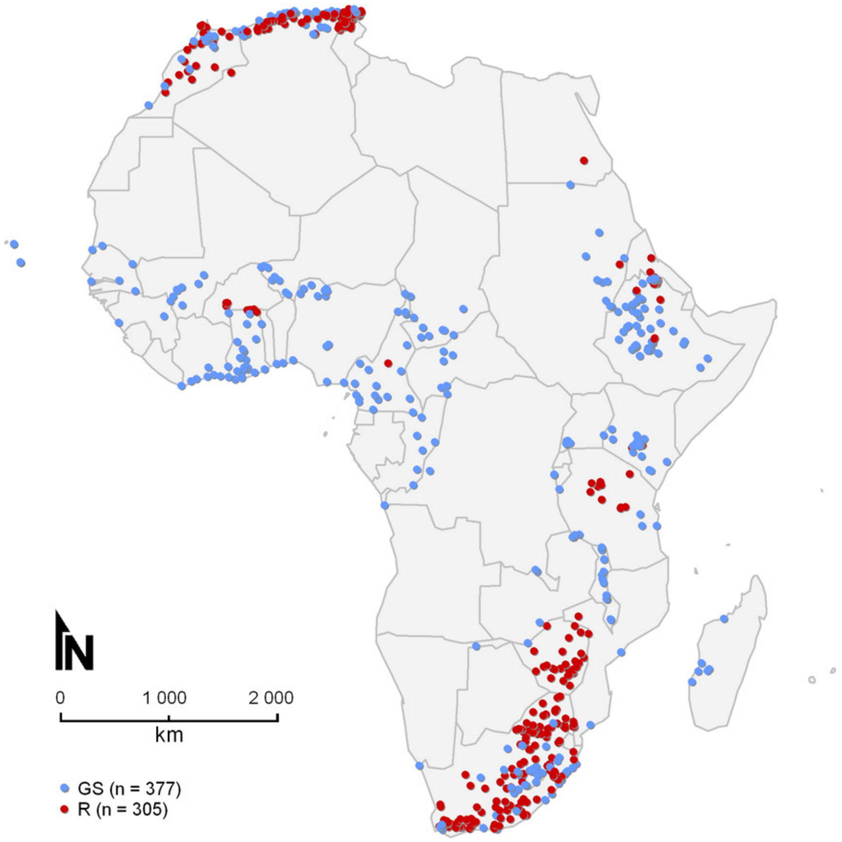

Fig. 1. Location of the outlets of all African catchments for which a sediment yield (SY) measurement is available and included in this study. 'GS' = SY was derived from gauging station measurements, 'R' = SY was derived from sedimentation rates in a reservoir. 'n' = number of catchments.

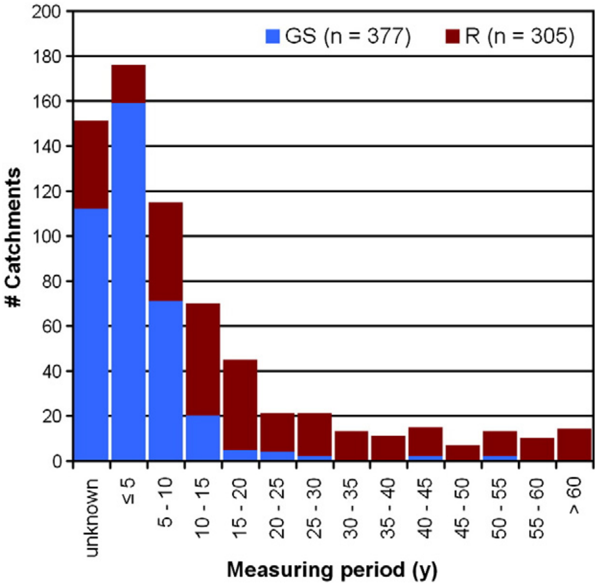

Fig. 2. Number of African catchments for which sediment yield (SY) data are available, according to the measuring period of the SY observation. A subdivision is made according to the measuring method: 'GS' = SY was derived from gauging station measurements (377 catchments) and 'R' = SY was derived from sedimentation rates in a reservoir (305 catchments).

Based on the criteria discussed in Section 2.1, about half of the SY observations were evaluated to have a 'good' or 'acceptable' data quality (Fig. 4). For 91 of the SY observations, the reliability was expected to be 'poor'. Especially the reliability of GS entries was mostly low or unknown (Fig. 4). As discussed in Section 2.1, uncertainties on these SY observations are often further increased by the corresponding short measuring period (e.g. Walling, 1984; Olive and Rieger, 1992; Vanmaercke et al., 2012; Fig. 2).

2.4. Catchment areas

Catchment areas for the collected SY data range between 0.02 and 3.8×10^6 km^2 (median: 998 km^2, average: 53,128 km^2; Fig. 5). Less than 22% of the catchments are smaller than 100 km^2, while only 12% is smaller than 10 km^2. Most of these SY observations for smaller catchments were derived from reservoir sedimentation rates (Fig. 5). Also SY data compilations for other regions in the world show that smaller catchments are clearly less well represented (e.g. Dedkov and Mozzherin, 1984; Jansson, 1988; de Araújo and Knight, 2005; USGS, 2008; Vanmaercke et al., 2011b). This is most likely explained by the fact that larger catchments (>100 km^2) are more relevant for planning water management at national scales and are therefore better represented in gauging station networks.

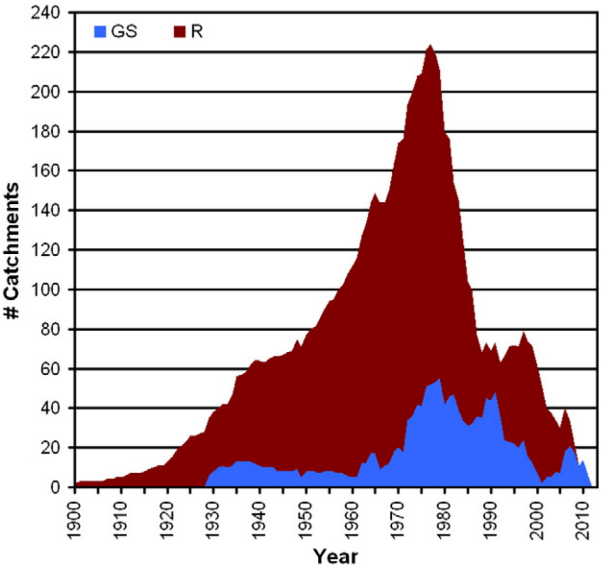

Fig. 3. Temporal coverage of the catchments with a sediment yield (SY) observation for which the start and end dates of the SY measurement were known (n = 495). A subdivision is made according to the measuring method: GS = SY was derived from measurements at a gauging station (250 catchments) and R = SY was derived from reservoir sedimentation rates (245 catchments).

Nonetheless, SY data from small catchments are also highly relevant for various purposes. For example, large numbers of micro-dams have been constructed throughout Africa in order to increase water availability (e.g. Rockström, 2000; Liebe et al., 2005; Haregeweyn et al., 2006; Adwubi et al., 2009). Reliable estimates of the expected sediment input into reservoirs are crucial when designing and implementing such projects. Smaller catchments are generally also more suitable than larger catchments to study impacts of various environmental conditions on sediment export, since larger catchments often have more heterogeneous characteristics and are commonly less sensitive to land cover changes or specific climatic events (e.g. Walling, 1983; Parkin et al., 1996; Trimble, 1999; Walling, 1999; Phillips, 2003; Dearing et al., 2006).

3. Observed sediment yields in Africa

The compiled SY observations for African catchments range between 0.2 and 15,700 t km^{-2} y^{-1} (median: 160 t km^{-2} y^{-1}, average: 634 t km^{-2} y^{-1}). However, SY values derived from reservoir sedimentation rates (median: 256 t km^{-2} y^{-1}, average 808 t km^{-2} y^{-1}) are generally higher than those obtained from gauging station observations (median: 114 t km^{-2} y^{-1}, average 493 t km^{-2} y^{-1}; Fig. 6). As discussed in Section 2.1, SY measurements from gauging stations generally do not include bedload and have a higher probability of underestimating the true SY, which may partly explain this difference.

Nonetheless, this difference may also be attributed to specific catchment characteristics and environmental conditions. For example, SY observations derived from reservoirs are mainly for catchments <10,000 km^2, while most SY data for larger catchments (>10,000 km^2) are based on gauging station measurements (Figs. 5, 6). In addition, Fig. 1 indicates important spatial differences in measuring method: most of the SY values derived from reservoir surveys were made in mountainous regions (i.e. the Rift Valley, Southern Africa and the Atlas region), while a majority of the gauging station observations were made in 'lowlands' (e.g. Western Africa). This pattern corresponds well with observed patterns in SY. When we classify all SY observations into three classes that contain each about one third of the SY observations, one can clearly notice that many of the lowest SY observations are located in Western Africa, while Southern and Eastern Africa are generally characterised by higher SY values (Fig. 7). The largest SY values were mainly recorded in the Atlas region and in Ethiopia. It is therefore likely that the difference between SY values derived from gauging station observations and those derived from reservoir sedimentation rates (Fig. 6) to some extent reflects regional differences of SY in Africa. This will be further investigated in Section 4.

4. Explaining the spatial variability of sediment yield in Africa

4.1. Methodology

4.1.1. Delineating catchment boundaries

For each of the catchments included in the database an attempt was made to delineate the catchment boundaries. This step was necessary to allow the extraction of various catchment properties that potentially explain the spatial variability of SY in Africa. Depending on the size of the catchment and local terrain conditions, catchment boundaries were (in order of preference) delineated from either SRTM 90 m DEMs (CGIAR,

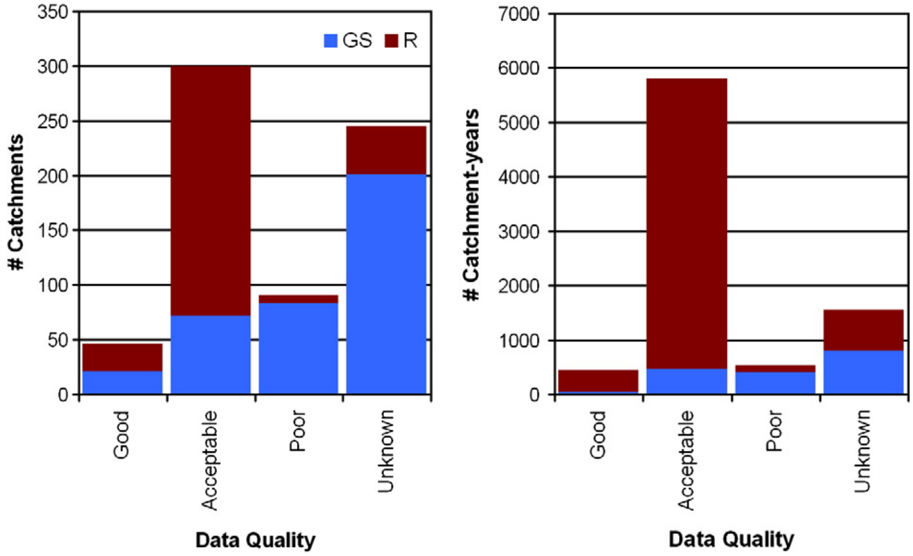

Fig. 4. Number (#) of catchments (left) and the corresponding number of catchment-years (right) according to the estimated quality of their sediment yield (SY) measurement. A subdivision is made according to the measuring method: 'GS' = SY was derived from gauging station measurements (377 catchments) and 'R' = SY was derived from sedimentation rates in a reservoir (305 catchments). A measuring period of 1 year was assumed for SY observations with an unknown measuring period.

2008), the 30 arc-second HydroSHEDS dataset (Lehner et al., 2006) or the 0.5° STN dataset (Vörösmarty et al., 2000). Catchment areas resulting from this delineation procedure did not always correspond to the catchment area reported in the original data source. These deviations can be attributed to several reasons: uncertainties on the estimated outlet location, errors and inaccuracies in the datasets used to delineate the watershed boundaries, and wrongly reported catchment areas in the original data source. Estimating the reliability of the obtained watershed boundaries therefore involved some expert judgement. However, as a general criterion, only catchments for which the delineated area deviated less than 20% from the originally reported catchment area and for which we were certain about the outlet location were considered for further analyses.

In total, catchment boundaries could be delineated for 507 of the 682 catchments (Fig. 8). The median deviation of the delineated area from the originally reported catchment area was 2.6%. The spatial distribution of the catchments for which the catchment boundaries could be delineated corresponds closely to the overall availability of SY data in Africa (compare Figs. 8 and 1). The 175 catchments for which the boundaries could not be accurately delineated were not considered in our further analyses.

4.1.2. Parameter selection

Several catchment characteristics were derived for each catchment for which the catchment boundaries could be delineated (Section 4.1.1). These characteristics describe the area, topography, lithology, seismic activity, climatic conditions and land cover of the catchments (Table 3). Most of these variables or similar ones have also been used in previous studies on spatial variation in SY or long-term erosion rates at the catchment scale (e.g. Montgomery and Brandon, 2002; Syvitski and Milliman, 2007; de Vente et al., 2011; Portenga and Bierman, 2011). In addition, we included variables to indicate whether a catchment is potentially influenced by large reservoirs (i.e. reservoirs included in the earlier published GranD database; Lehner et al., 2011) and whether the SY measurement corresponding to the catchment was derived from gauging station measurements or reservoir

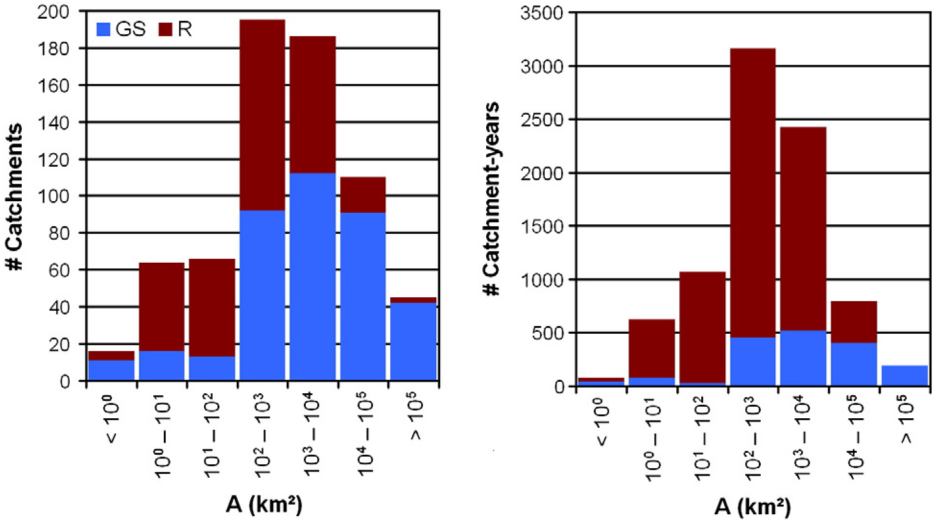

Fig. 5. Number (#) of catchments (left) for which sediment yield (SY) data are available and the corresponding number of catchment-years (right) according to the area (A) of the catchment. A subdivision is made according to the measuring method: 'GS' = SY was derived from gauging station measurements (377 catchments) and 'R' = SY was derived from sedimentation rates in a reservoir (305 catchments). A measuring period of 1 year was assumed for SY observations with an unknown measuring period.

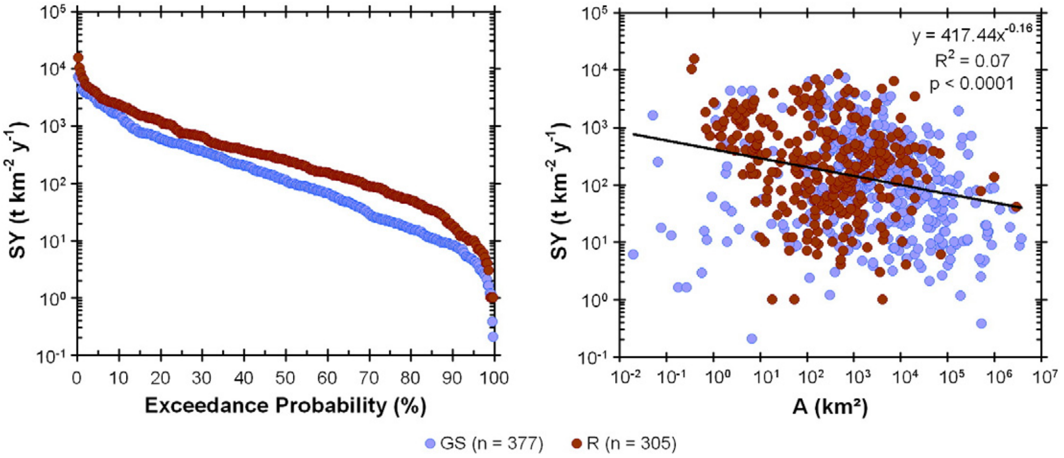

Fig. 6. Left: Exceedance probability of all observed African catchment yields (SY) reported in this study. Right: Scatter plot of these SY data and their corresponding catchment area (A). In both graphs, SY observations are subdivided according to their measuring method (GS = gauging station, R = reservoir). The regression (right) is based on all data (n = 682).

sedimentation rates (Table 3). Although more variables can be included, the variables listed in Table 3 were considered to be the most meaningful in the framework of this study. Several other variables (e.g. average height of the catchment, different measures to quantify land cover) were initially included but yielded no different results.

A comparison of environmental characteristics between the 507 selected catchments (Section 4.1.1) and the African continent shows that, although some differences in distribution exist, both cover the same range for most of the considered characteristics (Fig. 9). This indicates that the SY data used in this study are representative for the African continent.

4.1.3. Statistical analyses

The relevance of these variables in explaining differences in SY was explored by means of Pearson (partial) correlation coefficients. Partial correlation measures the degree of association between two variables, with the effect of other controlling variables removed (Fisher, 1924; Steel and Torrie, 1960). These (partial) correlation coefficients were calculated based on the log-transformed SY values. Where relevant, also log-transformed versions of the selected parameters (Section 4.1.2) were considered in the analyses. A similar approach was followed in earlier studies aiming to identify the factors controlling SY or erosion rates (e.g. Aalto et al., 2006; de Vente et al., 2011; Portenga and Bierman, 2011).

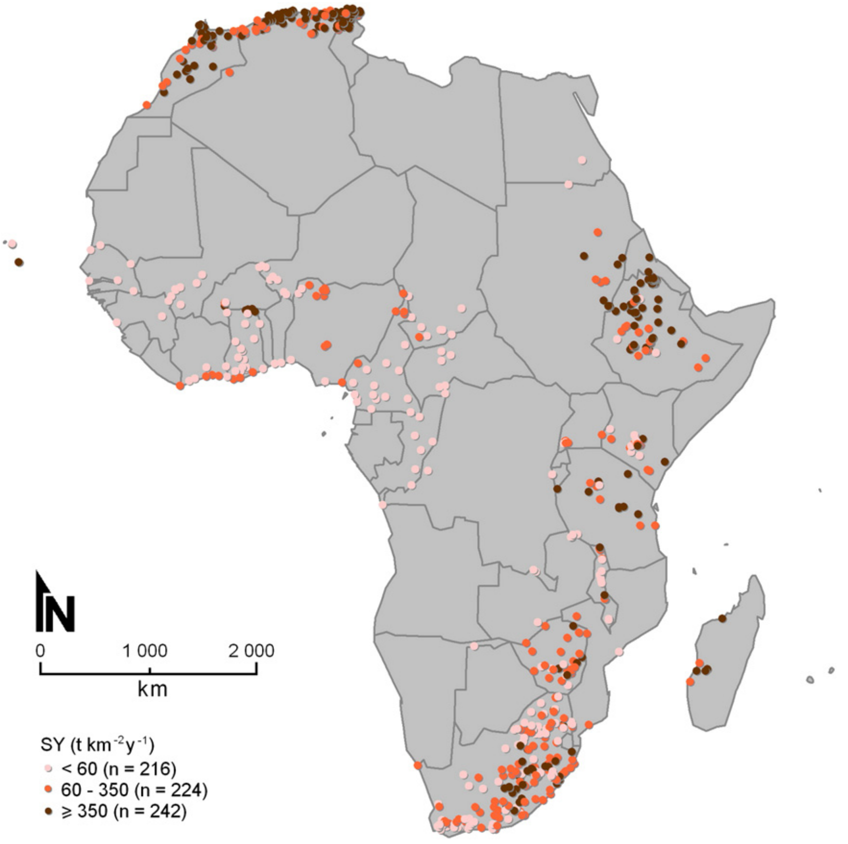

Fig. 7. Catchment sediment yield (SY) in Africa, based on all SY observations reported in this study. The subdivision in SY classes was made so that each class contains ca. one third of all the observations. Each dot corresponds to the outlet of a catchment for which SY was measured. 'n' = number of catchments.

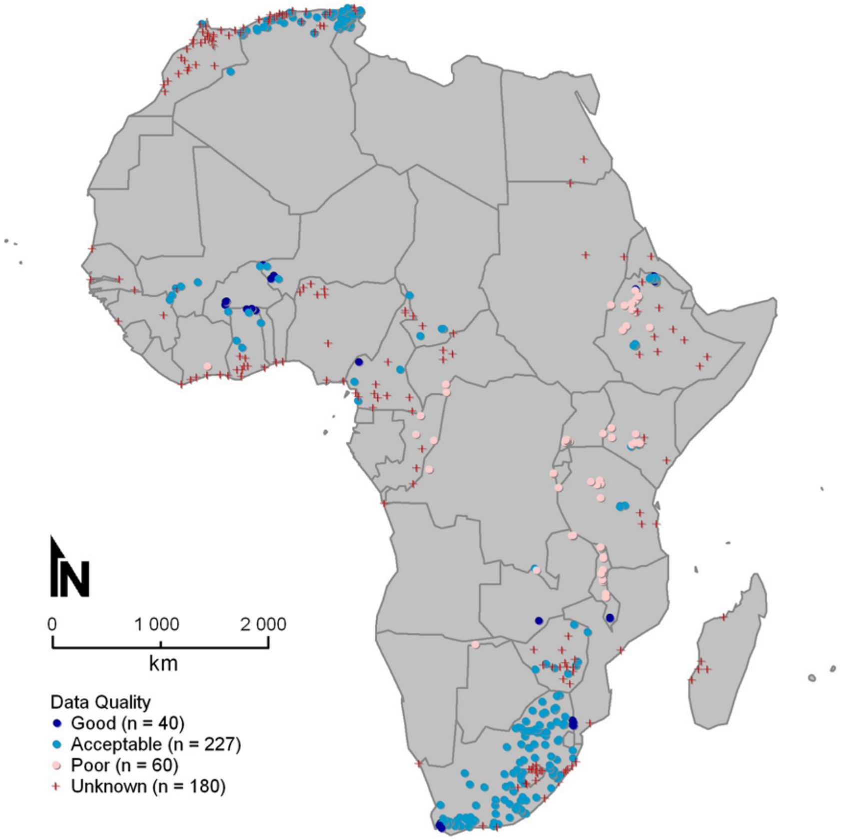

Fig. 8. Location of the outlets of the 507 catchments with available sediment yield (SY) observations for which the catchment boundaries could be delineated. Symbols indicate the estimated data quality of the SY observation. 'n' = number of catchments.

In addition, the potential importance of the considered parameters (Table 3) in explaining SY was explored by stepwise regressions, a commonly applied method where the selection of predictive variables is carried out by an automated procedure (Draper and Smith, 1998; Verstraeten and Poesen, 2001). The procedure works by generating an initial model and then evaluating (based on an F-statistic) if adding any of the potential variables would significantly increase the explanatory power of the model. If so, the variable is added. Likewise, it is checked if removing any of the included variables would result in a significant decrease of explanatory power. If not, the variable is removed again. The procedure ends when no single step further improves the model (Mathworks, 2013).

To obtain sufficiently robust results, this stepwise regression procedure was not applied to the entire dataset but to 10,000 randomly selected subsets containing between 30 and 70% of the original 507 catchments. This resulted in 10,000 different stepwise regression models. Evaluating the frequency with which variables were included in these models, allowed assessing the overall importance of these variables for explaining spatial differences in SY.

4.2. Factors controlling sediment yield

4.2.1. Main results

Of all variables considered (Table 3), PGA shows the strongest correlation with the natural logarithm (ln) of SY (Table 4). PGA (i.e. the expected Peak Ground Acceleration with an exceedance probability of 10% in 50 years; Shedlock et al., 2000) relates to the probability that an earthquake causes ground movement in the catchment and is a proxy for the degree of seismic activity in a catchment. Based on Fig. 10a, one can argue that this correlation is mainly attributable to one observation with a high SY and a PGA-value of $3.1\ \mathrm{m\ s^{-2}}$ (i.e. the SY of the Allalah river near Sidi Akacha, Algeria; FAO, 2008). However, this catchment has very little influence on the regression (removing this observation from the regression yields the following equation: $SY = 54.4e^{1.67PGA}$; $R^2 = 0.16$; $p < 0.0001$; $n = 506$). Overall, the distribution of PGA values for the considered catchments also agrees well with the distribution of PGA in Africa (Fig. 9; Shedlock et al., 2000).

Also the variables used to characterise topography generally show significantly positive correlations with ln(SY) (Table 4). Of all topographic measures, the natural logarithm of MLR (Mean Local Relief, i.e. a robust proxy for catchment slope, see Table 3) shows the strongest correlation with ln(SY) (Fig. 10b). Likewise, lithology (quantified by the scoring variable L; see Table 3) shows a significant and positive correlation with ln(SY) (Table 4; Fig. 10c).

Land cover, expressed as the areal fraction of tree cover (TreeCover; Defries et al., 2000) shows a significantly negative correlation with the natural logarithm of SY (Table 4; Fig. 10d). Since TreeCover represents a fraction and not an absolute value, this variable was not logarithmically transformed. Also catchment area correlates negatively with SY (Fig. 6), as do most of the considered climatic parameters (Table 4; Fig. 10e and f). Variables that express the intra-annual variability in rainfall and runoff (i.e. VarP and VarRo) did not show significant correlations with ln(SY).

Evidently, all these correlations should be interpreted with care, since several of the considered catchment characteristics are also inter-correlated (Table 4). For example, PGA shows significant correlations with L, MLR and several other topographic parameters. Likewise, rainfall and rainfall erosivity correlate negatively with many of the topographic measures. As earlier studies demonstrated, disentangling the importance of individual variables in explaining SY is often difficult (e.g. Verstraeten and Poesen, 2001; de Vente et al., 2011; Portenga and Bierman, 2011; Vanmaercke et al., 2011a,b). Nonetheless, some insight can be obtained from the partial correlation coefficients, i.e. the correlation between two variables that remains after correcting for one or

Table 3
Catchment characteristics calculated for each catchment for which the catchment boundaries could be determined ($n = 507$). Resolution indicates the original spatial resolution of the data layer from which the parameter was derived. 'N.A.' indicates not applicable.

Variable	Factor	Description	Derived from	Resolution	Units
A	Size	Originally reported catchment area.	Original source of the SY-data	N.A.	km^2
R	Topography	Relief, i.e. the maximum altitude difference within the catchment.	ERSDAC (2009)	30″ × 30″	m
MLR	Topography	Mean Local Relief, where local relief is the maximum altitude difference within a radius of 5000 m.	ERSDAC (2009)	30″ × 30″	m
Hstd	Topography	Standard deviation of the altitude within the catchment.	ERSDAC (2009)	30″ × 30″	m
L	Lithology	Catchment lithology erodibility factor, defined by Syvitski and Milliman (2007). Based on a global lithology map (Dürr et al., 2005), a score was assigned to each lithology, depending on their erodibility. Scores ranged between 0.5 for erosion-resistant rock types (e.g. acidic plutonic or metamorphic rocks) and 3 for very erodible lithologies (e.g. loess).	Dürr et al. (2005)	30′ × 30′	N.A.
PGA	Tectonics	Peak Ground Acceleration with an exceedance probability of 10% in 50 years.	Giardini et al. (1999), Shedlock et al. (2000)	6′ × 6′	m s^{-2}
T	Climate	Average (1961–1990) annual air temperature.	New et al. (2002)	10′ × 10′	°C
P	Climate	Average (1961–1990) annual rainfall.	New et al. (2002)	10′ × 10′	mm
VarP	Climate	Relative monthly rainfall variability. VarP was calculated as the difference between the wettest and driest month of the year, divided by the mean monthly rainfall. Minimum, maximum and mean monthly rainfall values were derived from average rainfall statistics for the period 1961–1990.	New et al. (2002)	10′ × 10′	%
RE	Climate	Average Rainfall Erosivity. RE-values were based on the Modified Fournier Index, calculated from monthly rainfall data for the period 1998–2008 and data from literature.	Vrieling et al. (2010)	15′ × 15′	MJ mm ha^{-1} h^{-1} y^{-1}
Ro	Climate	Estimated annual runoff depth, based on observed river discharges and simulated water balances.	Fekete et al. (1999)	30′ × 30′	mm y^{-1}
VarRo	Climate	Relative monthly runoff variability. VarRo was calculated as the difference between the highest and lowest estimated monthly runoff, divided by the average monthly runoff.	Fekete et al. (1999)	30′ × 30′	%
TreeCover	Land cover	Estimated percentage of the catchment that is covered by trees, as derived from 1992 to 1993 satellite data.	Defries et al. (2000)	30″ × 30″	%
VarNDVI	Land cover	Estimated intra-annual changes in vegetation cover, derived from average monthly NDVI-values for the period 1982–2000 (except 1994). VarNDVI was calculated as the difference between the maximum and minimum monthly NDVI, divided by the mean monthly NDVI value.	EDIT-CSIC (2007)	6′ × 6′	%
Reservoirs	Reservoir impacts	Boolean variable indicating if the catchment is potentially affected by large reservoirs (1) or not (0). Values were calculated by making an overlay between the catchment boundaries and the locations of reservoirs included in the GranD reservoir database.	Lehner et al. (2011)	N.A.	N.A.
Method	Measuring procedure	Dummy variable to indicate if the SY-value was derived from measurements at gauging stations (0) or from bathymetric surveys of a reservoir (1)	Original source of the SY-data	N.A.	N.A.

more controlling variables (see Section 4.1.3). Table 5 lists the partial correlation coefficients of the considered variables after removing the effect of all other variables that relate to other factors (see Table 3). These partial correlation coefficients show that seismic activity (expressed as PGA or ln(PGA)) remains clearly correlated with ln(SY) after controlling for all variables that relate to factors other than tectonics (i.e. area, topography, lithology, climate, land cover, reservoir impacts and measuring procedure). This strongly indicates that the observed correlations between SY and seismicity (Fig. 10a) are not merely a result of inter-correlations with other factors. Likewise, most of the topographic variables and tree cover show significant partial correlations with ln(SY) (Table 5). Contrary to the normal Pearson correlations (Table 4, Fig. 10f), ln(Ro) shows a highly significant positive partial correlation with ln(SY) after controlling for all variables related to non-climatic factors (Table 5). This suggests that also the average annual runoff depth explains some of the observed variation in SY after the effect of other factors is taken into account. On the other hand, other climatic variables and variables related to lithology, catchment size, reservoir impact, measuring procedure and variability in land cover only show a weak (often insignificant) partial correlation with ln(SY) (Table 5).

These findings were confirmed by the stepwise regression models applied to 10,000 randomly selected subsets of catchments (see Section 4.1.3). Of all considered variables, TreeCover and PGA were selected in more than 98% of all cases as an explanatory of SY (Fig. 11). ln(MLR) was selected in 87% of the cases, followed by the natural logarithm of the annual runoff depth (68%) and the measuring method (64%). All other variables were only selected for less than half of the models (Fig. 11).

4.2.2. Comparison with other studies

Most of these results concur with findings from other studies exploring the factors controlling SY and erosion rates. For example, the strong topographic control on SY has been identified in several studies (e.g. Milliman and Syvitski, 1992; Montgomery and Brandon, 2002; Aalto et al., 2006; Portenga and Bierman, 2011). Likewise, negative relationships between vegetation cover and SY or erosion rates have been reported before (e.g. Bednarczyk and Madeyski, 1996; Vanacker et al., 2007; Nadal-Romero et al., 2011; Portenga and Bierman, 2011).

While it is often expected that SY decreases with catchment area due to an increased probability of sediment deposition, previous studies pointed out that such relationships need to be interpreted with care as they are often, at least partly, spurious and a result of inter-correlations between A and other catchment properties (e.g. Walling, 1983; Verstraeten and Poesen, 2001; De Vente et al., 2007; Vanmaercke et al., 2011b). Also in this case, SY shows a significant negative correlation with A (Fig. 6), which becomes insignificant after controlling for the effects of other factors (Table 5). Likewise, ln(A) was chosen as an explanatory variable of ln(SY) in less than half of the stepwise regression models (Fig. 11). This indicates that the negative trend between SY and A for African catchments can be mainly attributed to the overall lower topography and degree of seismic activity in larger catchments compared to smaller catchments (Table 4) and that catchment area itself is of relatively limited importance for explaining spatial variability in SY.

Also the poor correlations between ln(SY) and the considered climatic variables concur with findings of earlier studies. Although it can be expected that higher rainfall depth and erosivity would result in

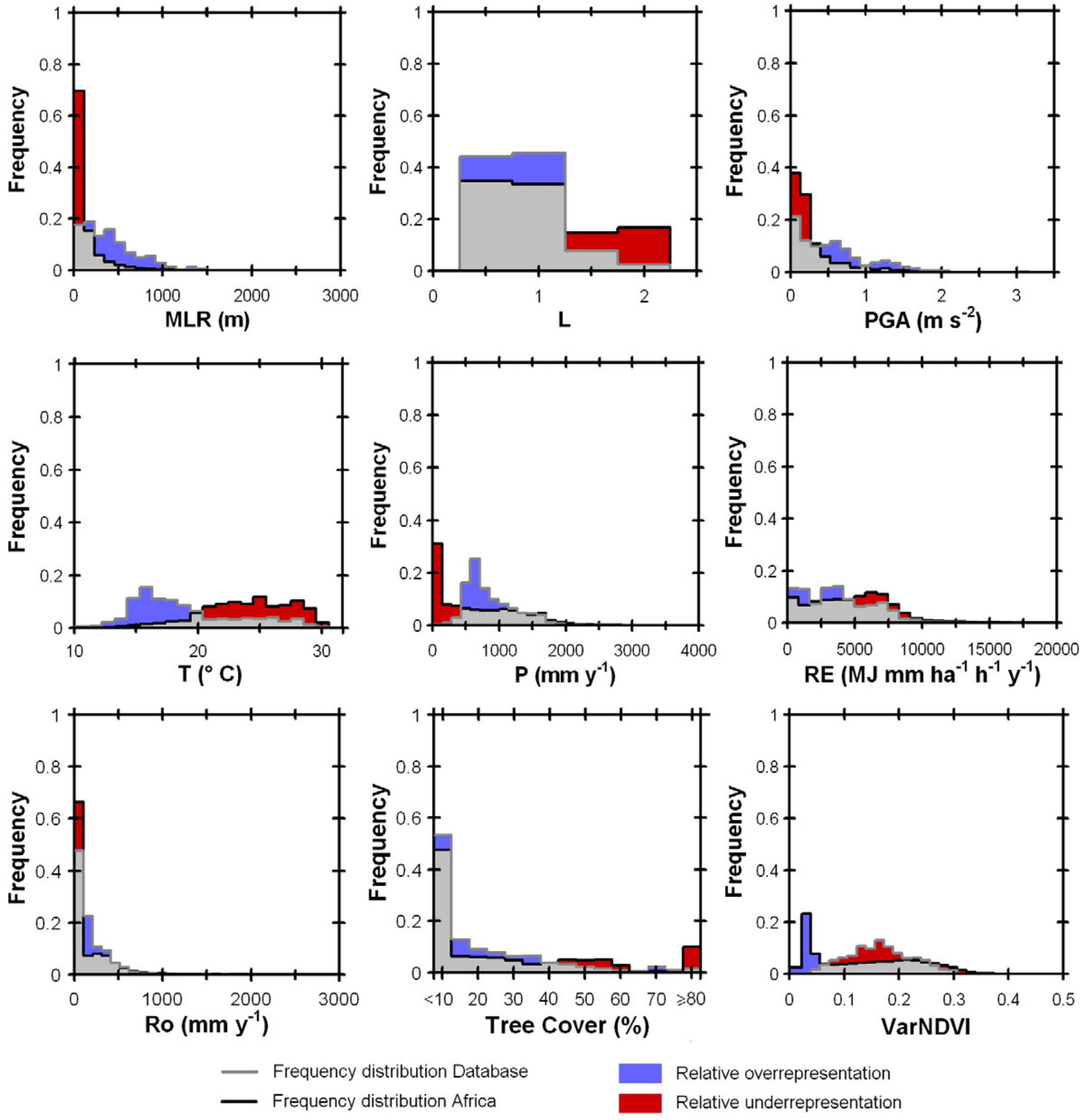

Fig. 9. Relative frequency distribution of catchment characteristics for the 507 catchments for which the catchment boundaries could be delineated ('database') compared to the frequency distribution of the same characteristic for entire Africa. See Table 3 for an explanation of the variables. Relative overrepresentation (underrepresentation) means that the selected catchments overrepresent (or underrepresent) the indicated range of the characteristic.

higher SY values, such trends are often not apparent for large datasets at the global or continental scale, due to the overriding effect of other parameters or interactions between rainfall and vegetation cover (e.g. Walling and Kleo, 1979; Jansson, 1988). Also Syvitski and Milliman (2007) did not detect any meaningful correlation between rainfall measures and the sediment load of rivers at a global scale and indicated that average air temperature might be a more meaningful measure of climatic impacts on SY. However, we observed no such effect (Table 5). The fairly limited range of temperatures for our African dataset might explain this.

Catchment runoff was found to have a significant but fairly limited impact on the spatial variability of SY (Table 5; Fig. 11). Likewise, this is in line with other studies reporting that runoff has only a relatively limited impact on average SY at regional or global scales (e.g. Aalto et al., 2006; Syvitski and Milliman, 2007; Vanmaercke et al., 2014a). It has been argued that temporal variability in rainfall, runoff and (linked to this) seasonal changes in vegetation cover can have an important impact on the sediment load of rivers (Walling and Webb, 1982; Hudson, 2003; Morehead et al., 2003; Moliere et al., 2004; Markus and Demissie, 2006; Alexandrov et al., 2007; Vanmaercke et al., 2010). However, none of the variables expected to reflect seasonal changes in rainfall (VarP), runoff (VarRo) or vegetation cover (VarNDVI) showed a convincing correlation with SY (Tables 4 and 5; Fig. 11). This may be attributed to the large uncertainties associated with these measures, as these provide only a rudimentary estimate of the seasonal fluctuations and not necessarily of the occurrence of flood events. These measures might be insufficient to reflect the often complex feedbacks between changes in climate, vegetation cover and sediment dynamics (Morehead et al., 2003; Vanmaercke et al., 2012). It could also indicate that, while very relevant for understanding sediment dynamics at local scales, temporal variability in rainfall, runoff or vegetation is less important for understanding spatial patterns of average SY values at the continental scale.

The fact that we did not detect an impact of upstream reservoirs on the spatial variability of SY (Tables 4 and 5; Fig. 11) may be explained by the similar reasons. It is well known that upstream reservoirs can significantly reduce SY (e.g. Vörösmarty et al., 2003; Syvitski et al., 2005; Walling, 2006). The lack of a clear correlation in our study may therefore

Table 4
Pearson correlation coefficients between all considered variables (Table 3) and with catchment sediment yield (SY) for the 507 catchment selected for detailed analyses. Values in bold are highly significant ($p < 0.0001$). Values in normal font are significant ($p < 0.05$). Correlations in italic are insignificant ($p > 0.05$). 'ln' indicates that the variable was logarithmically transformed.

	ln(A)	R	ln(R)	MLR	ln(MLR)	Hstd	ln(Hstd)	L	ln(L)	PGA	ln(PGA)	T	P	ln(P)	VarP	RE	ln(RE)	Ro	ln(Ro)	VarRo	TreeCover	VarNDVI	Reservoirs	Method	ln(SY)
ln(A)	1																								
R	**0.58**	1																							
ln(R)	**0.66**	**0.83**	1																						
MLR	**−0.26**	**0.30**	**0.42**	1																					
ln(MLR)	**−0.27**	**0.34**	**0.48**	**0.90**	1																				
Hstd	**0.33**	**0.88**	**0.78**	**0.59**	**0.59**	1																			
ln(Hstd)	**0.38**	**0.78**	**0.91**	**0.63**	**0.71**	**0.88**	1																		
L	*−0.03*	*0.06*	*0.08*	*0.08*	0.15	*0.03*	0.09	1																	
ln(L)	*0.02*	0.13	0.16	0.14	**0.21**	0.10	0.17	**0.97**	1																
PGA	**−0.26**	*0.02*	*0.05*	**0.31**	**0.35**	0.10	0.16	**0.20**	**0.19**	1															
ln(PGA)	**−0.19**	0.16	**0.20**	**0.35**	**0.43**	**0.26**	**0.34**	**0.22**	**0.21**	**0.84**	1														
T	**0.29**	−0.16	**−0.26**	**−0.64**	**−0.75**	**−0.35**	**−0.43**	**−0.36**	**−0.43**	**−0.24**	**−0.39**	1													
P	0.13	*0.03*	*0.01*	**−0.18**	**−0.24**	*0.02*	*0.02*	**−0.41**	**−0.45**	−0.12	*−0.08*	**0.37**	1												
ln(P)	*0.08*	*0.00*	*−0.03*	−0.16	**−0.22**	*0.00*	*−0.01*	**−0.42**	**−0.46**	−0.11	−0.09	**0.36**	**0.96**	1											
VarP	0.14	*−0.05*	−0.14	**−0.38**	**−0.42**	−0.17	**−0.24**	**−0.26**	**−0.25**	**−0.19**	**−0.33**	**0.57**	0.11	0.15	1										
RE	**0.22**	*−0.05*	−0.11	**−0.41**	**−0.48**	−0.13	**−0.18**	**−0.49**	**−0.52**	**−0.25**	**−0.29**	**0.63**	**0.79**	**0.78**	**0.52**	1									
ln(RE)	0.09	−0.10	−0.14	**−0.30**	**−0.35**	−0.15	**−0.19**	**−0.42**	**−0.44**	−0.16	**−0.24**	**0.47**	**0.63**	**0.76**	**0.48**	**0.78**	1								
Ro	0.14	0.10	0.13	*−0.04*	*−0.06*	0.13	0.14	**−0.23**	**−0.23**	−0.09	*−0.04*	0.16	**0.76**	**0.66**	*0.06*	**0.60**	**0.41**	1							
ln(Ro)	0.11	*0.09*	0.10	*0.00*	*−0.06*	0.11	0.11	**−0.25**	**−0.25**	−0.09	*−0.07*	0.14	**0.68**	**0.70**	0.11	**0.57**	**0.54**	**0.81**	1						
VarRo	*−0.01*	*−0.05*	*−0.08*	*−0.03*	*−0.04*	*−0.07*	−0.10	*0.08*	0.10	*0.04*	*−0.06*	*0.08*	**−0.38**	**−0.36**	**0.31**	**−0.19**	−0.14	**−0.34**	**−0.34**	1					
TreeCover	*−0.02*	*0.02*	*0.06*	0.13	*0.03*	0.09	0.12	**−0.39**	**−0.42**	*−0.02*	*0.07*	0.12	**0.52**	**0.52**	**−0.22**	**0.34**	**0.31**	**0.30**	**0.34**	**−0.30**	1				
VarNDVI	0.10	−0.13	**−0.21**	**−0.47**	**−0.40**	**−0.25**	**−0.31**	*−0.06*	*−0.07*	−0.13	**−0.23**	**0.38**	0.17	**0.26**	**0.51**	**0.45**	**0.48**	*0.05*	0.15	0.09	**−0.25**	1			
Reservoirs	**0.39**	**0.28**	**0.30**	*0.02*	*0.04*	**0.18**	**0.18**	*0.08*	0.14	**−0.19**	**−0.20**	−0.10	**−0.28**	**−0.27**	−0.11	**−0.25**	**−0.20**	**−0.19**	−0.14	0.16	−0.09	−0.14	1		
Method	**−0.37**	**−0.28**	**−0.28**	*0.02*	0.11	**−0.24**	**−0.24**	**0.20**	**0.20**	*−0.04*	*−0.02*	**−0.29**	**−0.49**	**−0.48**	**−0.23**	**−0.47**	**−0.39**	**−0.33**	**−0.32**	**0.22**	**−0.19**	−0.09	**0.19**	1	
ln(SY)	**−0.26**	0.11	*0.06*	**0.28**	**0.40**	**0.19**	0.16	**0.31**	**0.31**	**0.41**	**0.34**	**−0.36**	**−0.30**	**−0.26**	*−0.03*	**−0.32**	**−0.19**	−0.10	*−0.07*	*0.07*	**−0.39**	*0.03*	*−0.02*	**0.20**	1

be a result of the oversimplified manner with which the influence of reservoirs was evaluated (Table 3). Due to limitations in the available data, we only considered large reservoirs (Lehner et al., 2011) while also smaller ponds and reservoirs may have a significant impact on SY (e.g. Smith et al., 2002). Furthermore, our approach does not take into account the location of the reservoirs within the catchment, their trapping efficiency or the fact that some reservoirs were constructed after the SY measuring period. Nevertheless, it is also possible that the effects of reservoirs on SY are rather limited compared to other factors. Reservoir construction can easily lead to reductions in SY of a factor five (e.g. Walling, 2006). Nonetheless, such decreases remain relatively limited compared to the six orders of magnitude variation in SY for Africa (Fig. 6). Moreover, such reduction due to reservoir construction is often compensated for by a (re)activation of sediment sources, resulting in a quickly decreasing impact on SY downstream of the reservoir (e.g. Phillips, 2003).

Likewise, lithology explained little of the variation in SY (Table 5; Figs. 10c, 11). This too might be attributed to the fact that the lithology scoring variable used provides only a rough estimate of the erodibility (Table 3). Furthermore, the erodibility of rocks is also strongly controlled by the occurrence of fractures (e.g. Selby, 1980; Molnar et al., 2007; Koons et al., 2012), which are not considered by the scoring variable used. More detailed lithological descriptions and their degree of fracturing, as well as information on soil types and textures in the different catchments can be expected to explain more of the observed variability in SY. However, earlier studies also indicated that, compared to other factors such as topography and land cover, lithology has often only a secondary control on SY (e.g. Bruijnzeel, 2004; Aalto et al., 2006; Syvitski and Milliman, 2007; Vanmaercke et al., 2014a).

Finally, the strong control of seismic activity on seismic activity is noteworthy. PGA showed one of the strongest observed correlations with SY (Table 4, Fig. 10a) and remained one of the most important explanatory variables after controlling for other factors (Table 5, Fig. 11). As discussed in the Introduction, a growing number of studies show that seismicity can have a hitherto often neglected control on SY (e.g. Dadson et al., 2003; Cox et al., 2010; Hovius et al., 2011; Portenga and Bierman, 2011; Vanmaercke et al., 2014a,b). Nonetheless, Africa is one of the most stable continents in terms of seismic activity (e.g. Shedlock et al., 2000), while the variability in other factors (e.g. topography, climate, land cover) is very large. The fact that regional differences in seismicity have such a clear impact on observed SY can therefore be considered surprising.

Seismic impacts on SY are often attributed to earthquake-triggered landslides (e.g. Dadson et al., 2004; Hovius et al., 2011; Vanmaercke et al., 2014b). However, co-seismic landsliding mostly occurs only for earthquakes with a magnitude ≥ 4.3 (Malamud et al., 2004). Since high-magnitude earthquakes are relatively rare in Africa (ANSS, 2013), other explanations, such as the seismic weakening of rocks due to fracturing (e.g. Molnar et al., 2007; Koons et al., 2012) or an increased rate of river incision as a response to catchment uplift (e.g. Whittaker et al., 2010) are perhaps of greater importance. Overall, the linkages between seismicity and SY as well as the underlying erosion processes remain poorly understood. This is also illustrated by Cox et al. (2010) who noted that, due to unknown reasons, the spatial distribution of Lavakas (i.e. large gullies) on Madagascar mainly correlates with the occurrence of low-magnitude earthquakes.

4.3. Simulating spatial patterns of sediment yield in Africa

4.3.1. An African sediment yield model

Building on the results of our statistical analyses (see Section 4.2), a multiple regression model was constructed that simulates spatial variation in SY. The selection of variables and the type of relationship (exponential or power law) were based on the results of the normal and partial correlation analyses (Tables 4 and 5), the individual regression analyses (Fig. 10) and the stepwise regression analyses (Fig. 11),

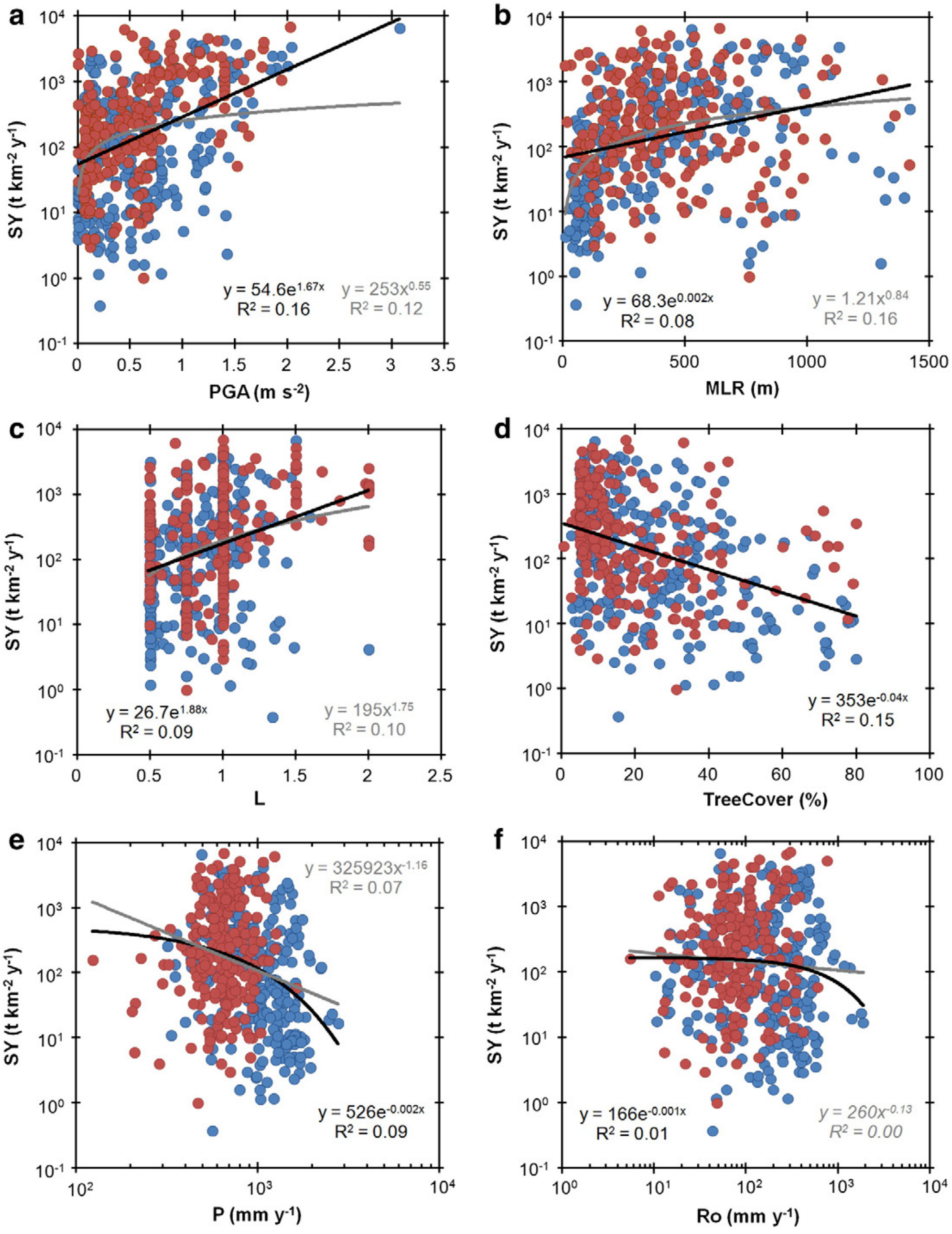

Fig. 10. Scatter plots of observed catchment sediment yield (SY) and some characteristics for the 507 catchments for which the catchment boundaries could be delineated (Fig. 8). Blue dots represent SY observations derived from gauging station measurements (n = 269), while red dots represents SY values derived from reservoir sedimentation rates (n = 238). See Table 3 for explanation of the catchment characteristics. Regressions are based on the pooled observations of both data types. The regressions in black show the best exponential fit, while regressions in grey show the best power fit. For (d) only an exponential relationship is shown since TreeCover represents a fraction. Equations in italic are insignificant at the 0.05 level (see Table 4).

showing that variability in SY is mainly controlled by seismicity, topography, vegetation cover and runoff ($n = 507$, $R^2 = 0.40$):

$$SY_{Pred} = 1.49 \times e^{1.24PGA} \times MLR^{0.66} \times e^{-0.05TreeCover} \times Ro^{0.24}. \quad (1)$$

With SY_{Pred} the predicted sediment yield in t km^{-2} y^{-1}, PGA the average expected Peak Ground Acceleration with an exceedance probability of 10% in 50 years, MLR the average height difference within a radius of 5 km, TreeCover the estimated percentage of the catchment covered by trees and Ro the estimated average annual runoff depth (see Table 3).

The model explains 40% of the observed variability of ln(SY) (Fig. 12). 74% of the predicted values deviate less than a factor five from their corresponding observed SY, while 88% deviate less than a factor ten. Hence, the unexplained variance remains relatively large. Apart from the parameters included in Eq. (1), several other variables showed a significant partial correlation with SY (Table 5). However, adding these to the model lead to only very small increases in explained variance. Moreover, 'Method' is the most frequently selected variable in stepwise regressions after runoff depth (Fig. 11). This indicates that the type of SY measurement (derived from gauging station measurements or reservoir sedimentation rates) is more important for explaining

Table 5
Partial correlation coefficient (partial r) and corresponding p-value for each considered variable with ln(SY) (i.e. the natural logarithm of the catchment sediment yield).
Each partial correlation was calculated by controlling for all variables that relate to different factors than the considered variable (see Table 3). For example: the partial r for PGA was calculated by controlling for all other variables except 'ln(PGA)'. Variables in bold show a very significant partial correlation ($p < 0.0001$). Variables in normal font show a significant partial correlation ($p < 0.05$). Variables in italic are insignificantly partially correlated ($p > 0.05$).

Variable	Factor	Partial r	p-Value
PGA	Tectonics	0.34	<0.0001
ln(PGA)	Tectonics	0.28	<0.0001
Hstd	Topography	0.28	<0.0001
R	Topography	0.27	<0.0001
TreeCover	Land cover	−0.27	<0.0001
ln(R)	Topography	0.23	<0.0001
ln(Hstd)	Topography	0.23	<0.0001
ln(MLR)	Topography	0.22	<0.0001
ln(Ro)	Climate	0.19	<0.0001
ln(RE)	Climate	0.14	0.0017
Ro	Climate	0.14	0.0026
MLR	Topography	0.13	0.0029
L	Lithology	0.12	0.0060
Method	Measuring procedure	0.12	0.0100
VarP	Climate	0.11	0.0136
RE	Climate	0.09	0.0467
ln L	Lithology	0.09	0.0539
ln P	Climate	0.08	0.0612
VarRo	Climate	−0.08	0.0672
VarNDVI	Land cover	0.08	0.0854
ln A	Size	−0.07	0.1291
P	Climate	0.04	0.3751
Reservoirs	Reservoir impacts	0.03	0.5257
T	Climate	−0.02	0.5957

variation in SY than catchment size, lithology, air temperature, climatic variability or other considered factors. Including these other significant variables would therefore involve the risk of overfitting the model. Also 'Method' was not included in the model since it does not reflect a catchment characteristic and added little to the explained variance (Fig. 12).

4.3.2. Unexplained variance

The relatively low fraction of variance explained by our model (Eq. (1); $R^2 = 0.40$) can be attributed to several reasons. Firstly, the observed SY data used are characterised by important uncertainties. A large fraction of the collected SY data has a poor or unknown quality, leading to potentially large deviations between the observed and true SY value (Section 2.3; Fig. 4). We tested if only using SY observations of 'good' or 'acceptable' quality resulted in better results. However, this would strongly compromise the representativeness of our model, since these data are mainly clustered in northern and southern Africa and very scarcely available for other parts of Africa (Fig. 8).

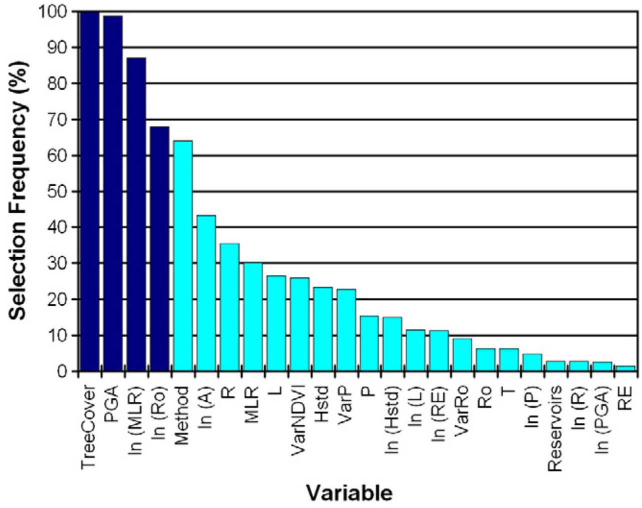

Fig. 11. Frequency with which potential explaining variables were selected during an automated stepwise regression procedure to predict ln(SY) for 10,000 randomly selected subsets containing between 30 and 70% of the original 507 catchments for which the catchment boundaries could be delineated (see Section 4.1). See Table 3 for explanation of the variables. Variables in darker colour were incorporated in the proposed regression model (Eq. (1)).

Secondly, also the variables included in the model (Eq. (1)) involve important uncertainties. Although MLR provides a robust proxy of topographic steepness on global or continental scales (e.g. Montgomery and Brandon, 2002), more refined measures based on more detailed DEMs may increase the explained variance (e.g. de Vente et al., 2009). Likewise, the fractions of tree cover in each catchment are only coarse-scale estimates based on satellite imagery obtained between 1992 and 1993 (Defries et al., 2000). These estimates may deviate significantly from the actual vegetation cover in the catchment during the SY measuring period. Also the PGA-values are subject to important uncertainties, associated with the earthquake inventories and extrapolation methods they are based on (Grünthal et al., 1999; Shedlock et al., 2000). Furthermore, the Ro-values used are only crude estimates of the long-term average runoff depth (Table 3; Fekete et al., 1999). Replacing these estimates by runoff measurements corresponding to the SY measuring period would most likely increase the explained variance. However, such observations were mostly unavailable.

Thirdly, also factors that are not considered by our model most likely influence SY. As discussed in Section 4.2.2, the lack of clear correlations between SY and catchment area, upstream reservoirs, lithology, temporal variations in climate or other factors may be attributed to the fact that they are only of limited importance compared to other factors, but also to the errors on the parameters used to quantify these effects. More accurate measures to express these factors may better explain some of the observed variability in SY.

These issues of uncertainty relate to a more fundamental problem that affects all empirical models aiming to predict SY or erosion rates. Namely, that spatially and/or temporary lumped parameters are often inadequate to describe the complex nature of erosion and sediment transport processes that depend not only on specific factors but also on their spatial patterns, their temporal changes and their interactions (e.g. Walling, 1983; Govers, 2011; Pelletier, 2012; de Vente et al., 2013). It can therefore be expected that more advanced models that take this spatial and temporal variability and interactions into account would result in higher prediction accuracies. However, this will only be true to some extent. Model errors are determined by a trade-off between errors in model concepts (i.e. simplifications of the actual situation) and errors in the input data used (de Vente et al., 2008; Govers, 2011; de Vente et al., 2013). Furthermore, the true unexplained variance of a model depends not only on model errors but also on errors on the observed SY values (Li, 1991; Van Rompaey et al., 2001). This is also indicated by the fact that more complex, spatially distributed and process-oriented models do not necessarily perform better in predicting SY than empirical models based on spatially and temporally aggregated parameters (e.g. de Vente et al., 2008; Govers, 2011; de Vente et al., 2013).

It should also be noted that the relatively low predictive power of our model ($R^2 = 0.40$; Fig. 12) is certainly not exceptional for a SY model (e.g. Meritt et al., 2003; de Vente and Poesen, 2005; Balthazar et al., 2012; de Vente et al., 2013). Since our model was based on very similar model concepts and input data as used in other empirical SY models, its somewhat lower model performance is most likely mainly due to the large uncertainties on many of the SY observations (Section 2.3).

4.3.3. Spatial patterns of sediment yield in Africa

Various studies have presented maps of expected SY values in Africa (e.g. Fournier, 1960; Strakhov, 1967; Walling and Webb, 1983; Walling, 1984; Pelletier, 2012). As indicated in the Introduction and already

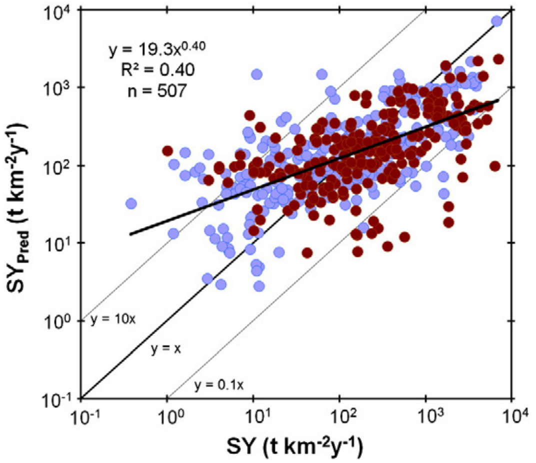

Fig. 12. Observed catchment sediment yield (SY), versus the corresponding predicted value (SY_{Pred}), using the regression model (Eq. (1)) for all catchments for which the catchment boundaries could be delineated (see Section 4.1).

pointed out by Walling (1984), many of these maps rely on very few SY observations and/or were often based on expert judgement without a thorough analysis of the factors controlling SY.

Despite its uncertainties, our model allows for a better insight into the spatial patterns of SY in Africa. Eq. (1) was applied to the gridded datasets of PGA, MLR, TreeCover and Ro and aggregated the result to a 50 × 50 km^2 resolution (roughly corresponding to the resolution Ro, i.e. the coarsest data layer; Table 3). A comparison of the resulting simulated SY map with all available SY measurements indicates very similar patterns (Fig. 13).

Based on seismicity, topography, land cover and runoff (see Section 4.3.1) our model predicts relatively high SY values along the Rift Valley and Madagascar, while central and South-western Africa and the Sahara are generally characterised by low SY values. The highest predicted SY values occur in the Atlas mountains and the northern part of the East African Rift Valley. This corresponds well with the observed SY values (Fig. 13).

While the average of all available SY observations for Africa equals 634 t km^{-2} y^{-1} (Section 3), the average simulated SY for the entire African continent is only 42 t km^{-2} y^{-1} (Fig. 13). The latter value closely corresponds to the estimated area-specific sediment flux of African rivers to the oceans before the impact of large dams (43 ± 8.3 t km^{-2} y^{-1}; Syvitski et al., 2005) and further indicates that our model (Eq. (1)) provides realistic estimates of the overall magnitude and spatial variability of SY in Africa (Fig. 13). The large difference between the average observed SY and the average expected SY of the African continent indicates that SY observations in Africa are biased towards erosion-prone conditions and areas. This is also evident from Fig. 9, showing that regions with high MLR, high PGA, significant Ro and low TreeCover values are somewhat overrepresented, compared to the rest of Africa. Nonetheless, most of these over-represented regions with high SY-values are also characterised by high population densities and face important population increases during the next decades (e.g. North-western Africa, the Ethiopian highlands, the Lake Victoria region; UN-ESA, 2011). Therefore, the overall low simulated average SY-value for Africa certainly not implies that problems related to SY are unimportant in Africa.

5. Conclusions

Africa has been largely underrepresented in previous studies aiming to understand the factors controlling SY at regional and continental scales (e.g. Table 1). By means of an extensive literature review on SY observations in Africa, we addressed this research gap. We compiled and georeferenced SY measurements for 682 African catchments (comprising more than 8340 catchment years of observations). With the exception of some countries, SY measurements are available for most of the populated regions of Africa (Fig. 1). Nonetheless, data availability remains relatively low compared to other continents (see Section 2.2). Furthermore, SY observations derived from gauging stations measurements are often based on short (<5 years) measuring periods and subjected to important uncertainties (Figs. 2 and 4). SY values

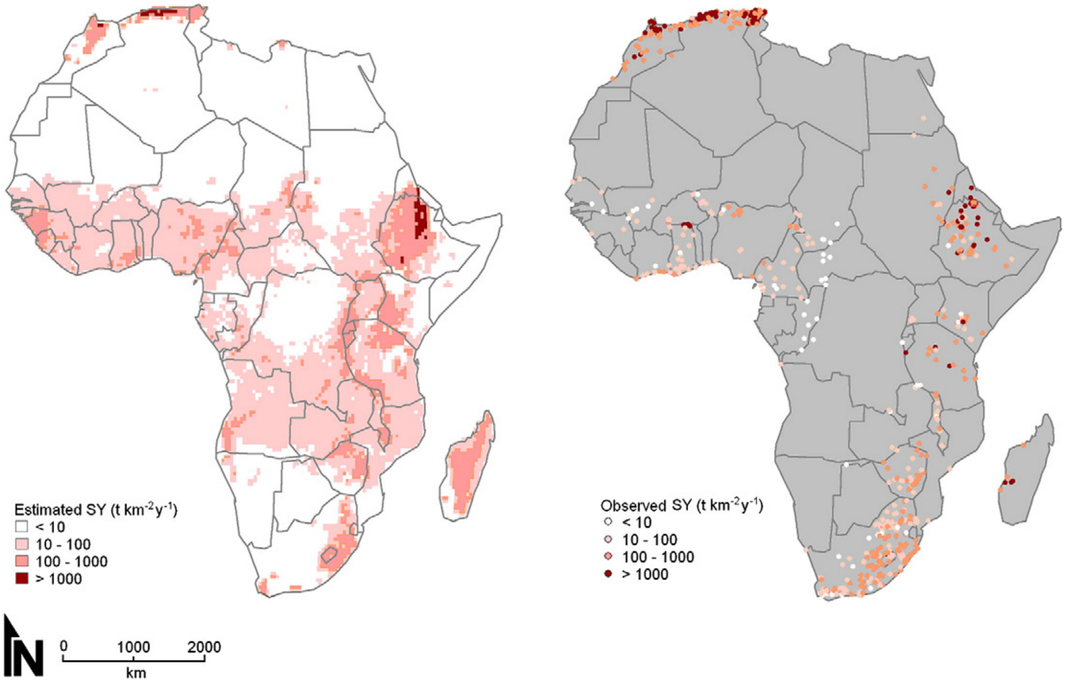

Fig. 13. Left: Estimated spatial patterns of sediment yield (SY) in Africa, obtained by applying Eq. (1) to gridded datasets (Table 3) and resampling the obtained pixel-values to a 50 × 50 km^2 resolution. Right: Observed catchment sediment yields at their outlet location according to the same classification as the left map for all catchments with available SY observations (n = 682).

derived from reservoir sedimentation rates are generally more reliable, but unavailable for large parts of Africa (Fig. 1).

The available SY observations display clear regional patterns: the Atlas mountains and the Rift region are generally characterised by relatively high SY values, while rivers in western and central Africa have generally lower SY values (Fig. 7). Extensive (partial) correlation analyses showed that these spatial patterns are best explained by differences in seismic activity, topography, vegetation cover and runoff. Combining these four factors resulted in a model that explains about 40% of the observed variation in SY (Eq. (1); Fig. 12). The large fraction of unexplained variance is probably attributable to the large uncertainties on many of the SY measurements, errors on the used predictive variables and the fact that other potentially relevant factors are not considered by our model. Nonetheless, this model was capable to simulate the spatial patterns of observed SY in Africa fairly well (Fig. 13).

These results have important implications. During the coming decades, Africa faces large population increases and important climatic changes. The fact that differences in SY at the continental scale are significantly correlated to tree cover and runoff indicates that these changes and their impact on land cover may have significant impacts on the sediment load of African rivers. Since high sediment loads form a potential threat to many existing or planned reservoirs, such changes may also threaten the future water availability in Africa. Likewise, they may affect the ecology of various aquatic systems in Africa.

Also the fact that seismicity explains a significant part of the observed variation in SY is important. A growing number of studies show that seismic activity can have important but hitherto often neglected impacts on contemporary erosion rates and SY. Nonetheless, most of these studies focus on regions that are seismically very active or on regions with strongly contrasting degrees of seismic activity. In Africa, however, both the differences and overall degree of seismicity are limited. It is therefore noteworthy that seismic activity still has such a clear impact on the spatial variation of SY in Africa, despite the large variability in climate, land cover and other factors. The mechanisms explaining this impact are currently poorly understood, but may be related to the seismic weakening of surface lithologies, tectonically induced changes in river base levels or (to a limited extent) earthquake-triggered landsliding. Nevertheless, this result indicates that seismic activity should not be neglected in studies focussing on SY at regional scales.

Further research is needed to quantify and understand the processes through which tectonic activity affects SY. Likewise, more detailed analyses that take into account the effects of lithology, soil characteristics, upstream reservoirs, weather conditions and land cover in a spatially (and temporally) explicit way may contribute to the development of more accurate SY models. Such models will be an important tool for addressing the hydrological challenges which Africa is facing. The dataset collected in the framework of this study may be an important aid in developing such models.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2014.06.004.

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