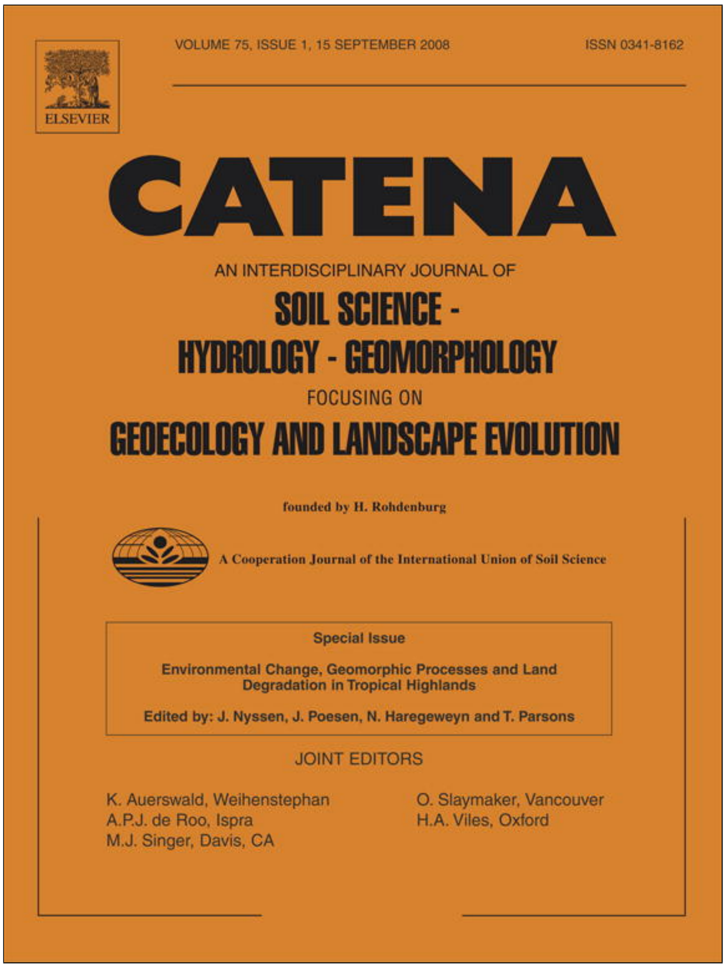
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Sediment yield variability in Northern Ethiopia: A quantitative analysis of its controlling factors

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ABSTRACT

In Tigray-northern Ethiopia, lack of sediment yield data and appropriate methodologies for predicting sediment yield have contributed to poor planning resulting in rapid sedimentation in reservoirs and storage capacity loss. The objectives of this study were: (1) to assess the spatial variability of absolute sediment yield (SY) and area-specific sediment yield (SSY) and to identify their controlling factors for 11 representative catchments and (2) to develop models to predict sediment yield. We quantified sediment yield from reservoir sediment surveys and studied the role of bio-physical characteristics of the catchments and their interactions in controlling SY and SSY variability.

The average SSY for 11 reservoirs was 9.89 t ha^{-1} y^{-1} with a standard deviation (S.D.) of ±4.46 t ha^{-1} y^{-1}, which can be considered as a large spatial variation in SSY among the catchments. Total drainage length (TDL) and the proportion of the catchment area that is treated with soil and water conservation (SWC) practices are the strongest variables controlling the variability of SY and the SSY, respectively. Interactions between controlling factors were found: i.e. SWC practices and average catchment slope (Av_slope) (r=0.80), SWC and proportion of cultivated land (CUL) (r=−0.64) and CUL and Av_slope (r=−0.81). SWC practices were found to be less implemented in catchments with a relatively high CUL-value and having moderately steep topography.

Best results were obtained with the SY regression model with a high model efficiency (ME=0.88). The SSY model had a reasonable ME of 0.66. Therefore, the SY model allows a better prediction of SY in the planning phase of new reservoirs in Northern Ethiopia. However, such models need new calibration if they are to be used beyond the region where they were developed and they do not allow spatially-distributed input and output.

1. Introduction

In northern Ethiopia, particularly in Tigray, rainfall is strongly seasonal and erratic. As a result, there is seasonal (about 8 months) moisture stress that hampers rain-fed agriculture (ILRI-CGIAR, 2004). Therefore, agricultural development through irrigation has been a priority for the Ethiopian Government during the last decade. To achieve this goal, the Regional Government of Tigray established in 1994 the "Commission for Sustainable Agriculture and Environmental Rehabilitation for the Tigray Region (Co-SAERT)". The commission targeted to bring food self-sufficiency in the area mainly by development of irrigated agriculture through planning, designing and construction of ca. 500 dams within ten years (SAERT, 1994). However, the construction of the dams did not proceed as planned. Up to 2003, only 54 dams were built because of different problems such as sedimentation, excessive seepage, lack of appropriate dam sites and technical problems. Sediment deposition in those reservoirs is a serious off-site consequence of soil erosion that threatens their sustainability.

Reservoir sediment surveys in northern Ethiopia by Haregeweyn et al. (2006) showed that the severity of the sedimentation problem is high: six of the eleven studied reservoirs were experiencing extreme sedimentation so that their economic life will be reduced to half of the design life. The rapid sedimentation is mainly associated with poor planning of the reservoirs for the expected sediment yield during the design phase, which in turn is attributed to lack of sediment yield data and lack of appropriate methodologies to predict sediment yield.

Accurate estimation of sediment yield makes it possible to adapt the dimensions of planned constructions so that the actual life time of

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the reservoir can meet the requirements. Furthermore, knowledge of the factors controlling sediment yield can help to design sediment control strategies within the catchment and to select the best locations for dam construction. In Ethiopia, most studies on soil erosion rates and sediment yield has dealt only with soil loss rates due to rill and inter-rill erosion, mostly from runoff plots (SCRP, 2000; Haregeweyn and Yohannes, 2003). On the other hand, sediment and runoff yield data for some of the trans-boundary river basins are also available (e.g. Blue Nile, Awash, and Wabi Shebele) (Humphreys et al., 1997; REDECO, 2002; Nyssen et al., 2004). Scientific studies that investigated the principal controlling factors of sediment yield at catchment level in this part of the world are not available (Nyssen et al., 2004).

Because of a lack of site-specific data, area-specific sediment yield (SSY) values between 8.00 and 12.00 t ha^{-1} y^{-1} were assumed across the Tigray region in various technical reports, but no exact source was provided. In other cases, estimation of sediment yield has been based on the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965). However, this model was not designed for sediment yield estimation at catchment level (Hudson, 1995) since it does not consider sediment transport, deposition and the input of point sediment sources such as gullies, channel erosion and mass movements.

Basically, four major categories of sediment yield models can be distinguished that were developed world-wide to estimate soil loss and sediment yield. These include: (1) semi-quantitative (e.g. Verstraeten et al., 2003), (2) regression/empirical (e.g. Verstraeten and Poesen, 2001a), (3) conceptual models (e.g. Young et al., 1989) and (4) physics-based models (e.g. Flanagan et al., 2001).

Generally, the simplicity of the model decreases and yet the accuracy of the prediction increases as we go from model classes (1) to (4). Semi-quantitative models have been tested for the Northern Ethiopian catchments by Haregeweyn et al. (2005) and were found to provide a fairly accurate estimate of sediment yield with limited data input. However, such models suffered from some degree of subjectivity during factor rating and they provide only limited quantitative information especially on the sources of sediment, the role of the controlling factors and on the interaction between factors. Wheater et al. (1993) reported that the application of empirical/regression models can partly solve these limitations.

Sediment yield is the net result of soil erosion and sediment deposition processes and is thus dependent on those variables that control erosion and sediment delivery. Soil erosion is dependent on local topography, soil, climate and vegetation whereas sediment delivery is influenced by catchment morphology, land use and drainage network, form and density (Walling, 1994; Williams, 1975) and human practices. Spatial variability in sediment yield may, therefore, reflect the spatial variability in catchment properties and human activities. These relations are often summarized in single regression models like the relationship between catchment area and sediment yield (Walling, 1983; Milliman and Syvitski, 1992; Nyssen et al., 2004; de Vente et al., 2007); or in multiple regression models using more than one catchment characteristic (Hadley et al., 1985; Neil and Mazarari, 1993; Verstraeten and Poesen, 2001a).

Therefore, the objectives of the study were: (1) to assess the spatial variability of sediment yield in northern Ethiopia and to identify its controlling factors using empirical analysis and (2) to develop sediment yield predictive models.

2. Materials and methods

2.1. Study area and study catchments

This study was carried out in Tigray-northern Ethiopia (Fig. 1). Tigray is one of the Ethiopian regional states, located in the northern part of the country between 12° 15′N and 14° 50′N and 36° 27′E and 39° 59′E (Fig. 1) and has a total area of 5 007 800 ha (out of which 19% is suitable for cultivation) and a population of more than 3.8 million (CSA, 2001). The climate can be characterized as tropical semi-arid (Virgo and Munro, 1978) with an annual rainfall ranging from 450 mm in the north, east and central zones to 980 mm in the southern and western parts of the region. Most rainfall occurs within July, August and September. The topography of the region mainly consists of highland plateaus up to 3900 m a.s.l., which are dissected by gorges. However, the north western part of the region is characterized by lowlands with elevations as low as 500 m a.s.l. The highlands support a high population density (40–70 persons km^{-2}; FAO, 2006) and are seriously affected by land degradation due to their long cultivation history (starting 3000 BC, Hurni, 1989; Bard et al., 2000; Nyssen et al., 2004), steep topography and erosive rains. In contrast, the lowlands are sparsely populated and have soils that are less eroded and exploited (TFAP, 1996).

Fifty four reservoirs have been built in Tigray since 1994 with the aim to bring food self-sufficiency in the region through irrigation agriculture (Haregeweyn et al., 2006). The reservoirs' storage capacity ranges between 0.1 and $3.1 \cdot 10^6$ m^3 and catchment area between 36 and 5200 ha. Eleven representative catchments for topography, human activities and lithology, which are located in a radius of 120 km from Mekelle, Tigray's regional capital, were selected for this study (Fig. 1). The salient features of the eleven studied reservoirs/catchments are given in Table 1.

2.2. Assessment of sediment yield

Here, the term sediment yield refers to the total sediment outflow from a catchment measured at the point where the reservoir is located for a specific period of time. It can be expressed in absolute terms as sediment yield (SY) or as area-specific sediment yield (SSY). Sediment yield data can be obtained either by monitoring or by using adaptable models. Monitoring can be done using various techniques such as: (1) using sediment rating curves, calibrated by simultaneously monitoring the suspended sediment load and the runoff discharge and (2) measuring sediment volumes in ponds, lakes or reservoirs.

Reservoir surveys usually offer several important advantages as compared to continuous monitoring (Morris and Fan, 1998): they do not depend on a continuous monitoring programme; measurement during peak flood discharge is not required, they are much less costly than the continuous fluvial sediment monitoring and they represent the total load (suspended and bed load). However, there are sources of errors and limitations associated with this type of measurement, such as the estimation of the trap efficiency and dry bulk density (Verstraeten and Poesen 2002). In this study, sediment yield data for the 11 catchments were derived from reservoir sediment survey.

Sediment yield (SY and SSY) was calculated after Verstraeten and Poesen (2001b) as:

$$\mathrm{SY} = \frac{100 * \mathrm{SM}}{\mathrm{STE} * Y} \tag{1}$$

$$\mathrm{SSY} = \frac{\mathrm{SY}}{A} \tag{2}$$

where

SY = absolute sediment yield (t y^{-1}), SM = total sediment mass deposited in the reservoirs (t), STE = sediment trap efficiency (%), Y = age of the reservoir (years), SSY = specific sediment yield (t $ha^{-1}y^{-1}$), A = catchment area (ha), with,

$$\mathrm{SM} = \mathrm{SV} * \mathrm{dBD} \tag{3}$$

and SV = the measured volumetric sediment input in the reservoir (m^3), dBD = the area-weighted average dry bulk density of the sediment (t m^{-3}).

Sediment thickness was measured by observing sediment profiles (up to 4 m deep) in pits dug along transects within the reservoirs, with

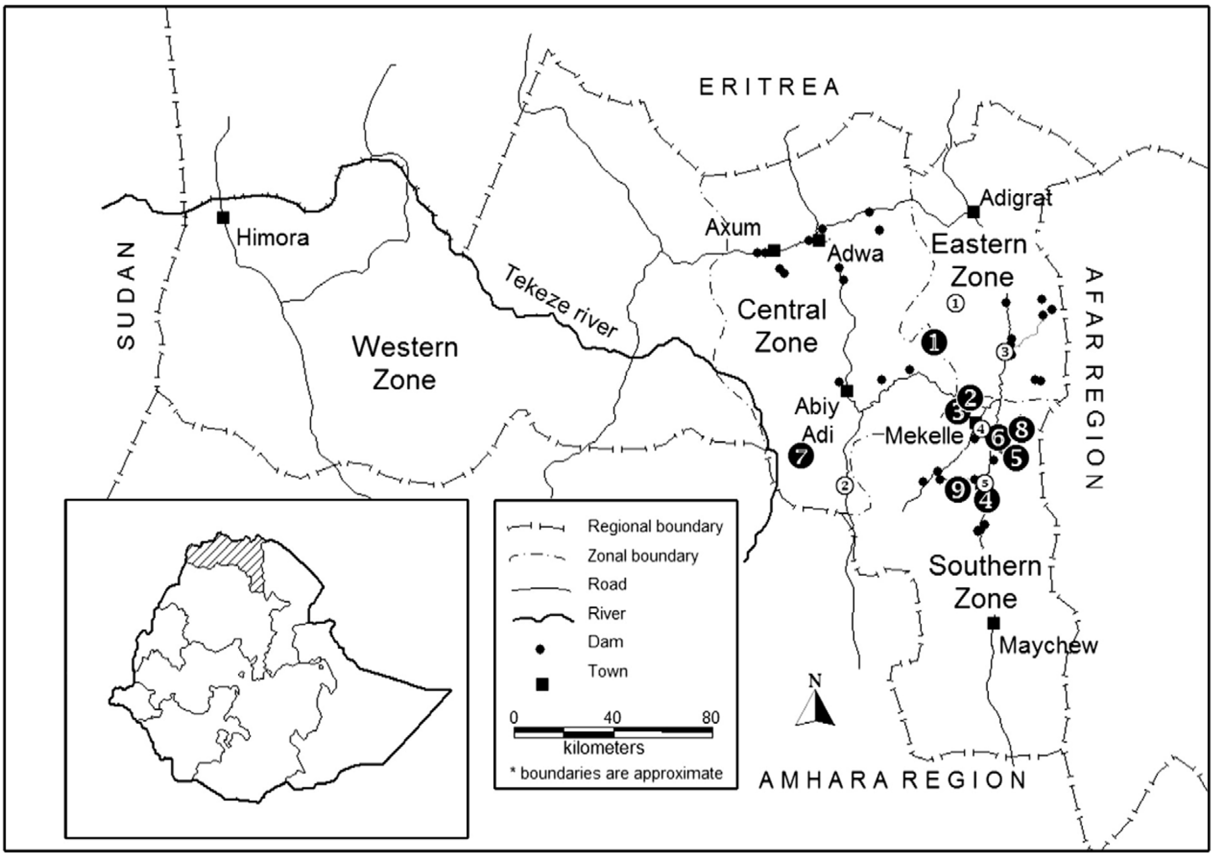


Fig. 1. Location of the study area (Tigray) in northern Ethiopia and the studied reservoirs. Dots represent reservoirs visited, numbers with black fill represent reservoirs for which sediment yield was measured: 1 Gindae, 2 Gereb Shegel, 3 Sewhimeda, 4 (Gereb Segen, Grashitu, Mejae, Maideli, Gum Selasa), 5 Adiakor, 6 Adihilo, 7 Agushella, 8 Endazoey, 9 Adikenafiz. Numbers without fill represent rainfall stations: 1 Hawzen, 2 Yechila, 3 Wukro, 4 Mekelle airport, 5 Adigudom. The stations are owned and run by Ethiopian Meteorological Authority. Sewhimeda and Agushella reservoirs were not included in this study for the reason of unique rock mining activities in 10% of the Sewhimeda catchment and due to a lack of a topographic map for Agushella.

15 to 39 pits per reservoir depending on the size and shape of the original bottom surface of the reservoir (see example in Fig. 2). Sediment volume was computed by constructing a Digital Elevation Model (DEM) with a resolution of 1 m using TIN interpolation in IDRISI® and taking sediment thickness as the *z* value.

Sediment trap efficiency (STE) is the percentage of the total incoming sediment which is retained in the reservoir. The STE was assessed based on one season field monitoring (summer, 2003) and interviewing local farmers about the history of the reservoir. All reservoirs are less than seven years old and spillage never occurred for most of the reservoirs since their construction.

Sediment yield data are generally expressed in mass units (t). Hence, the measured sediment volumes need to be converted to sediment masses using representative values of sediment bulk

Table 1
Characteristics of 11 selected micro dam reservoirs and their respective catchments in Tigray

No.	Reservoirs	*A* (ha)[a]	Location, UTM (Zone P37)[a] X	Y	Elevation (m)[a]	LS volume (10^3 m^3)[b]	DS volume ($10^3 m^3$)[b]	LE (y)[b]	RA when full (ha)[b]	DH (m)[b]	Dam CL (m)[b]	Catchment soil texture[a]
1	Adiakor	292	562,188	1,482,025	2210	510	6	30	4	210	10	Silt loam
2	Adihilo	72	561,327	1,486,172	2308	110	4	9	2.5	177	11	Silt clay
3	Adikenafiz	1430	544,194	1,465,274	2167	670	60	31	12.86	514	16	Sandy loam
4	Endazoey	140	570,660	1,489,184	2432	180	20	25	4.05	227	12	Sandy clay loam
5	Gereb Segen	435	553,619	1,465,412	2100	340	22	25	11.7	208	15	Clay
6	Gereb Shegel	858	548,945	1,502,177	1921	1000	200	n.a.	17.11	378	20	Loam
7	Gindae	1187	536,297	1,522,368	1979	790	142	20	13.5	483	20	Clay loam
8	Grashitu	511	555,102	1,460,677	2084	170	18	20	6.72	477	9	Clay
9	Gum Selassa	2414	558,642	1,463,566	2146	1900	476	30	48	428	14	Clay
10	Maideli	1050	556,547	1,461,226	2130	1580	270	27	38.6	486	15	Clay
11	Mejae	256	555,021	1,458,530	2135	300	13	40	6	266	14	Clay

A: catchment area, LS: 'live' storage volume, DS: 'dead' storage volume; LE: designed life expectancy; RA: reservoir area; DH: dam height; CL: dam crest length; n.a.: not available. Catchment area was delimited using GPS readings and processed in MapInfo®; soil texture was based on laboratory analysis and using USDA Soil Textural Classification System and average slope was derived from Elevation Model in IDRISI®.

[a] This study.

[b] Various reports of SAERT and REST—see extensive list in Haregeweyn (2006).

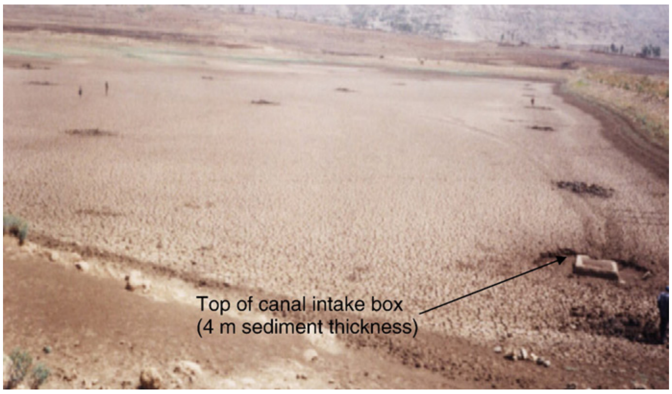


Fig. 2. Adikenafiz reservoir. The top of the inlet canal is clogged due to excessive sediment deposition and is shown cleared from sediment.

density. Dry bulk density (dBD) was determined by the gravimetric method. Undisturbed representative sediment samples were taken using core rings (volume 10^{-4} m^3) from 8–12 sampling sites per reservoir (near the dam axis, in the middle, at the side and inlet of the reservoir), and at a minimum of two different depths in the profile pit. Details on reservoir sediment survey can be found in Haregeweyn et al. (2006).

2.3. Catchments parameters

Bio-physical catchment characteristics that might control the spatial variability of sediment yield were collected. These were grouped into three major categories: (1) topography, (2) human activities and (3) soils and geology. Each category has multiple inputs: thirteen parameters for topography, three for human activities, and nine for soils and geology. Rainfall was not considered in this analysis as it is not significantly varying among the catchments. Details of the type of studied parameters, data sources and methods of derivation are shown in Table 2.

2.3.1. Topography

The topographic parameters were either directly derived from a DEM (e.g. catchment slope), from field mapping (gully cross-section characteristics) or indirectly computed using already established equations. The best available DEM for the whole study area was the SRTM 3 arc-second shuttle DEM from the USGS EROS data centre (http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html). This DEM was mosaiced, re-projected, and data gaps were filled by application of a mean focal filter. Details on the topographic parameters, data sources and methods of data derivation are given in Table 2.

2.3.2. Human activities

Parameters expressing human activities include land use practices, soil and water conservation practices and roads and footpaths. Details on the human practice parameters, data sources and methods of data derivation are given in Table 2.

Morris and Fan (1998) reported that over much of the earth's surface, the most significant determinant for land degradation is human activity. Hurni (1990) estimated soil loss rates by water erosion for different land uses in Ethiopia and the highest erosion rate was obtained in cropland (i.e. 42 t ha^{-1} y^{-1}). Based on measurements conducted on 202 plots, Gebremichael et al. (2005) found that the introduction of stone bunds in Tigray decreased soil loss by sheet and rill erosion from farmers' field by 68%.

Sidle et al. (2006) studied the role of roads in Southeast Asia and found that both landslide and surface erosion fluxes along roads are typically one to more than two orders of magnitude higher compared to undisturbed steep land forests. High storm runoff from roads is caused by the generation of infiltration-excess overland flow on compacted surfaces and the interception of subsurface flow at road cuts; these altered pathways increase surface erosion and accelerate the delivery of storm runoff to streams. Discharge nodes from roads facilitate the connectivity of runoff and sediment to headwater streams.

2.3.3. Soils and geology

Soil erosion and sediment yield are affected by properties such as texture of the soils and sediment. The texture of the eroded materials is associated with the sources of erosion. Coarse materials are usually produced by stream-bank and gully erosion, while the fine materials are often from sheet and rill erosion (Bartholic, 2004). Less runoff

Table 2
Investigated catchment properties, data sources and methods of data collection in Tigray

Data layers	Controlling variables	Data collection, sources and data derivation
Topographic variables	Digital elevation model (DEM, 20 m by 20 m)	http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html Processed in IDRISI®.
	Catchment area (A, ha)	Field mapping using GPS.
	Minimum elevation (H_{min}, m)	DEM
	Maximum elevation (H_{max}, m)	DEM
	Height difference between the outlet and the highest point in the catchment (HD, m)	DEM
	Main drainage length (MDL, km)	Field mapping of main drainage length (water course) using GPS.
	Total drainage length (TDL, km)	Field mapping of all drainage lengths (water courses) using GPS.
	Horizontal length between the outlet and the remotest point in the catchment divide (HL, m)	DEM
	Relief length ratio (RLR)	$\mathrm{RLR} = \frac{\mathrm{HD}}{\mathrm{HL}}$ (USDA, 1972)
	Hypsometric integral (HI)	$\mathrm{HI} = \frac{(\mathrm{Hmean}-\mathrm{Hmin})}{(\mathrm{Hmax}-\mathrm{Hmin})}$ (Strahler, 1964)
	Average catchment slope (Av_slope, %)	DEM
	Average main drainage slope (MDS, %)	$\mathrm{MDS} = \frac{\mathrm{HD}}{\mathrm{MDL}}100$ (Verstraeten and Poesen, 2001a)
	Form factor (FF)	$\mathrm{FF} = \frac{A}{\mathrm{HL}^2}$ (Suresh, 2002)
	Drainage density (DD)	$\mathrm{DD} = \frac{\mathrm{TDL}}{A}$ (Morris and Fan, 1998)
	Gully channel characteristics	Field mapping and measuring length (Lg), average width (Wg) and average depth (Dg) of gully channel using meters, meter sticks and GPS.
	Total gully volume for a catchment (TGV, m^3)	$\mathrm{TGV} = \sum_{n=1}^{n} \mathrm{Lg}{*}\mathrm{Wg}{*}\mathrm{Dg}$, where n is number of gully segments.
	Specific gully volume for a catchment (SGV, m^3 km^{-2})	$\mathrm{SGV} = \frac{\mathrm{TGV}}{A}$
Human activities	Land use mainly cultivated land (CUL, % of A)	Field mapping of land use using GPS
	Density of roads and foot path (RD, km km^{-2})	Field mapping of roads and foot paths using GPS
	Areal-coverage of soil and water conservation (SWC, % of A)	Field mapping of soil water conservation practices using GPS
Geology and soils	Limestone (LS, % of A)	
	Sandstone (SS, % of A)	
	Shales (SL, % of A)	Field mapping of surface geology using GPS.
	Dolerite (DT, % of A)	
	Area-weighted proportion (%) of clay, silt, sand catchment soils	Field mapping catchment soil units using GPS and representative soil sampling. Hydrometer method for texture analysis and the area-proportion was determined in MapInfo®.
	Simple average proportion (%) of clay, silt and sand in the sediment	Sampling representative sediment profile pits in the reservoir. Hydrometer method for laboratory texture analysis.
	Enrichment ratios of clay (ER_clay), silt (ER_silt), sand (ER_sand)	Catchment soil and reservoir sediment texture analysis See Eq. (4).

energy is needed to transport finer particles (i.e. silt and clay) than coarse materials (i.e. sand). Thus, sand is more likely deposited in the transport process, while eroded silt and clay particles are more easily transported downstream. As a result, it is expected that high sediment yields will result in sediment with high clay and silt content. Moreover, Lahlou (1988) demonstrated the importance of surface geology in controlling the spatial variability of sediment yield on Moroccan catchments.

Walling (1983) suggested that sediment delivery ratio which is defined as the ratio of sediment yield to total erosion in the catchment may be calculated from the fractions of clay in the sediment and in the soil as:

$$\mathrm{SDR}\ (\%) = C_{\mathrm{soil}}\ (\%)/C_{\mathrm{sed}}\ (\%) \tag{4}$$

where

SDR = sediment delivery ratio (%), C_{soil} = the clay content in the soil (%), C_{sed} = the clay content in the sediment (%).

Eq. (4) is an inverse presentation of the enrichment ratio (ER) which is defined as the ratio of the concentration of the constituent in the sediment to the concentration of the constituent in the soil (Wan and El-Swaify, 1998).

In order to characterize the soils in terms of major soil textures (clay, silt and sand), both catchment soils and deposited sediment were analyzed. For the deposited sediment, 5 to 11 pits per reservoir were dug and representative composite samples per pit were taken. In the catchments, sediment contributing areas were identified in which smaller land units (polygons) were delineated where the soil texture characteristics were thought to be homogenous taking into account parent material, land use and slope. From each polygon, the 20 cm topsoil was sampled based on a systematic random sampling. The number of sampling places varied from 6 to 28 per catchment. Soil texture was analyzed using hydrometer analysis (Gee and Bauder, 1982) in Holetta Research Centre Soil Laboratory (Ethiopia). Finally, area-weighted average values were calculated for each textural class in the catchment.

Surface geology was mapped in the field using GPS and an area-proportion of each geological unit was calculated using Mapinfo®. The available 1:250 000 geological map from Ethiopian Geological Studies was not detailed enough at the scale of this study.

2.4. Statistical analysis

Pearson's pair-wise correlation was used between all pairs of both dependent and independent variables to establish whether variables are related linearly. The association was tested for significance at <0.05 and 0.01 levels in SAS® (SAS, 2002). Moreover, the multi-collinearity between the independent variables was assessed.

Two multiple-regressions models for predicting SY and SSY were fitted in a step-wise multiple regression technique and tested for significance at <0.05 and 0.01 levels. A default steeping method criteria i.e. probability of F at 0.05 and 0.1 for entry and removal were adopted, respectively.

In case of multi-collinearity between dependent variables, the variance inflation ratio (VIF) was used as an index to exclude either of the variables that are less important to the model performance. As the variance inflation factor increases, so does the variance of the regression coefficient, making it an unstable estimate. Large VIF values are an indicator of multi-collinearity. A partial correlation which is a correlation that remains between two variables after removing the correlation that is due to their mutual association with the other variables was also assessed.

In ideal conditions, regression models need to be validated, which is mostly done by splitting the dataset into two parts, one for model development and one for model validation. In this case, however, the Jackknife method (Shao and Tu, 1995) was used for validation, as is done for cases of small datasets (Bazzoffi, 1996; Verstraeten and Poesen, 2001a; de Vente et al., 2005; Haregeweyn et al., 2005). Eleven test models were constructed, with the same independent variables, each of which excluding one reservoir at a time and after which the model was applied for predicting SY and SSY for the remaining reservoirs. The observed sediment yield of the excluded catchment was compared to the predicted value of the corresponding test model.

Model performance was evaluated by using Nash and Sutcliff's Model Efficiency (ME) and the Relative Root Mean Square Error (RRMSE), calculated as follows:

- Model Efficiency (ME) Nash and Sutcliff (1970)

$$\mathrm{ME} = \frac{1-\sum_{i=1}^{n}(Q_i-P_i)^2}{\sum_{i=1}^{n}(Q_i-Q_{\mathrm{mean}})^2} \tag{5}$$

where

ME = model efficiency, n = number of observations, Q_{mean} = the mean observed value, Q_i = the observed value, P_i = the predicted value.

The value of ME can range from −∞ to 1 and represents the proportion of the initial variance accounted for by the model. The closer the value of ME approaches 1, the more efficient is the model. Negative values of ME indicate that the model produces more variation than could be observed i.e. the model is inefficient.

- Relative Root Mean Square Error (RRMSE) (Van Rompaey et al., 2001):

$$\mathrm{RRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_i-P_i)^2}}{\frac{1}{n}\sum_{i=1}^{n}Q_i} \tag{6}$$

where

RRMSE = Relative Root Mean Square Error, Q_i = observed value, P_i = predicted value, n = number of observations.

- Values for RRMSE range from 0 to ∞. The closer the RRMSE approximates zero (= the perfect model), the better the model performance.

3. Results and discussion

3.1. Specific sediment yield variability

Sediment yield data for the 11 catchments, calculated from the reservoir sediment survey, are presented in Table 3. The specific sediment yield varies spatially between catchments with a mean value of 9.89 t $\mathrm{ha^{-1}\ y^{-1}}$ and a standard deviation (S.D.) of ±4.46 t $\mathrm{ha^{-1}\ y^{-1}}$.

The magnitude and range of SSY values in this study area are high as compared to global and regional datasets. DFID (2004) shows that African and world median SSY are 2.99 and 2.52 t $\mathrm{ha^{-1}\ y^{-1}}$, respectively. The same study presented SSY data for 17 Tanzanian catchments in which the average SSY was computed at 6.20 t $\mathrm{ha^{-1}\ y^{-1}}$, for catchment areas ranging between 160 and 4000 ha. Generally, the SSY values in our study catchments and in the Ethiopian highlands (Nyssen et al., 2004) are high compared to data compiled for various regions in the world (Fig. 3). The high SSY magnitude in Ethiopia can be generally attributed to accelerated erosion rates resulting from intense human activities (Bard et al., 2000; FAO, 1986), erosive rain (Nyssen et al., 2005) and steep topography.

The SSY data for the 11 catchments were plotted in Fig. 4 together with SSY database for a range of Ethiopian river basins compiled by Nyssen et al. (2004) ($A=10^2$ to $3\cdot10^8$ ha; $n=20$), REDECO (2002) ($A=10^4$ to 10^5 ha; $n=34$) and Humphreys et al. (1997) ($A=10^3$ to 10^7 ha; $n=67$). Those data were, however, mostly derived from suspended sediment measurements. However, based on the

Table 3
Sediment yield data for 11 catchments in Tigray

No.	Reservoirs	SV (10^3 m^3)	SM (10^3 t)	Age (y)	STE (%)	SY (t y^{-1})	SSY (t ha^{-1} y^{-1})
1	Adiakor	5	6	5	100	1161	3.97
2	Adihilo	2	3	5	100	684	9.50
3	Adikenafiz	109	110	6	95	19,305	13.50
4	Endazoey	4	5	5	100	973	6.95
5	Gereb Segen	12	15	3	100	5140	11.82
6	Gereb Shegel	19	21	5	100	4180	4.87
7	Gindae	56	72	5	100	14,438	12.16
8	Grashitu	36	39	5	85	9283	18.17
9	Gum Selassa	111	112	7	90	17,767	7.36
10	Maideli	67	70	5	98	14,359	14.29
11	Mejae	6	8	5	100	1580	6.17
	Average	39	42	5	97	8079	9.89
	S.D.	41	42	1	5	7213	4.46

SV: total sediment volume; SM: total sediment mass; STE: sediment trap efficiency; SY: absolute sediment yield; SSY: specific sediment yield; S.D.: standard deviation.

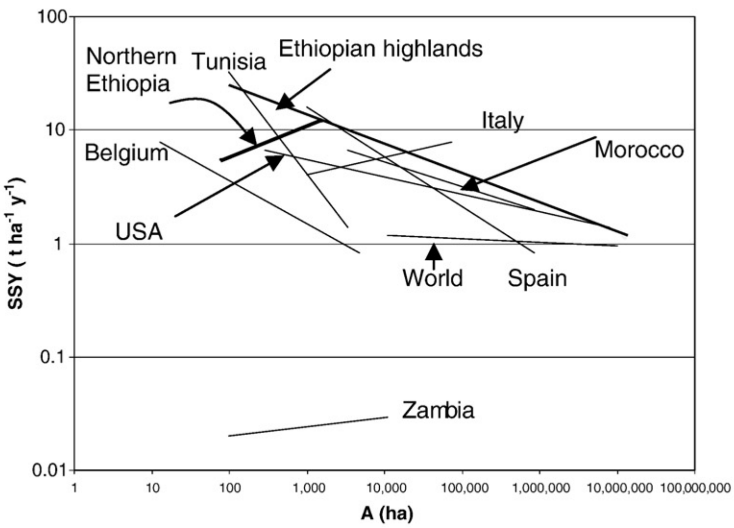
frequency of sampling, only 34 Ethiopian rivers are found to have reliable sediment yield data. Fig. 4 shows also that the suspended sediment measurements are available for catchment areas larger than 3000 ha. No information is available for smaller catchments except for this study and the limited dataset compiled by Nyssen et al. (2004). Moreover, the SSY values are larger in our study area. The higher SSY values might be explained by various factors: i.e. (1) the smaller size of catchment area in this study and hence less probability for sediment deposition within the catchment, (2) the variability in bio-physical factors controlling sediment delivery and (3) errors associated with the method of sediment yield assessment from suspended sediment data. Suspended sediment measurements take into account only fine fractions and their accuracy is affected by the frequency of sampling. As a result, this method is less accurate and less reliable than reservoir sediment yield surveys (Walling, 1983; Morris and Fan, 1998; REDECO, 2002; Verstraeten and Poesen, 2002).

3.2. Factors controlling sediment yield variability

3.2.1. Sediment yield and topographic characteristics

3.2.1.1. Sediment yield and catchment area. Among the catchment properties (Table 4), area is one of the parameters that explains part of the variation in absolute and specific sediment yields. A significant positive correlation ($r=0.86$) was observed between absolute SY and catchment area (Table 5).

The relation between SSY and catchment area is also positive, though statistically insignificant ($r=0.12$, Table 5). A positive correlation between SSY and A was only observed in few cases like the case of



Country/region Equation		r^2 and n
USA (Dendy and Bolton, 1976)	$SSY = 15.7A^{-0.16}$	n.a.
Spain (Koninckx, 2000 in Verstraeten and Poesen, 2001a)	$SSY = 281.25A^{-0.4243}$	$r^2 = 0.17$;n = 60
Morocco (Lahlou, 1988)	$SSY = 169.2A^{-0.252}$	$r^2 = 0.59$; n = 15
Central Belgium (Verstraeten and Poesen, 2001a)	$SSY = 25A^{-0.40}$	$r^2 = 0.64$; n = 26
World (Fleming, 1969)	$SSY = 1.83A^{-0.04}$	n.a.
Zambia (Sichingabula, 1997)	$SSY = 0.017A^{0.081}$	n.a.
Italy (Van Rompaey et al., 2005 cited in de Vente and Poesen, 2005)	$SSY = 103.6A^{0.28}$	$r^2 = 0.05$; n = 44
Tunisia (Albergel et al., 2000)	$SSY = 2027A^{-0.64}$	$r^2 = 0.20$; n = 23
Ethiopian highlands (Nyssen et al., 2004)	$SSY = 2595A^{-0.29}$	$r^2 = 0.59$; n = 20
Northern Ethiopia (this study)	$SSY = 0.005A + 6$	$r^2 = 0.36$; n = 9

Fig. 3. Relationship between catchment area (A, ha) and specific sediment yield (SSY, t ha^{-1} y^{-1}) for various regions. Exception is made for the units in the equation by Nyssen et al. (2004) i.e. A (km^2) and SSY (t km^{-2} y^{-1}). Updated after Verstraeten and Poesen (2001a) and de Vente and Poesen (2005). References cited in this figure: Dendy and Bolton, 1976; Fleming, 1969; Sichingabula, 1997; Albergel et al., 2000.

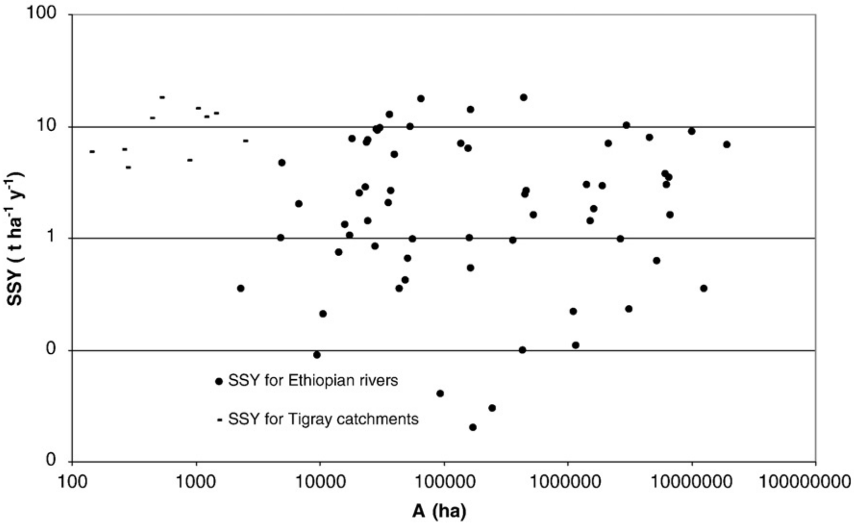


Fig. 4. Sediment yield data for Ethiopian rivers as compiled from various sources. The data were obtained from suspended sediment measurements in 67 rivers (Humphreys et al., 1997) throughout Ethiopia and from reservoir sediment surveys of 11 rivers in northern Ethiopia (this study).

the Turkish catchments (de Vente et al., 2006), the Italian catchments (de Vente and Poesen, 2005) and of the Zambian catchments (Verstraeten and Poesen, 2001a) (Fig. 3). The positive correlation in this study might be explained by the positive correlation between SSY and (1) height difference (HD) between the outlet and the highest point in the catchment, (2) total drainage length (TDL) and (3) specific gully volume (SGV) (Table 5). The HD within the catchment represents the potential energy available for soil erosion and TDL reflects a high sediment transport connectivity and potential river channel erosion as an important source of sediment (Poesen et al., 2003). de Vente and Poesen (2005) and de Vente et al. (2007) illustrate and discuss in detail how the relationship between catchment area and sediment yield is scale dependent and, furthermore, depends strongly on active erosion processes.

In Ethiopia, empirical modelling of sediment yield at catchment scale is limited except for few attempts such as by Nyssen et al. (2004)

Table 4
Catchment properties for 11 studied catchments in Tigray

No.	Catchment	SY (t y^{-1})	A (ha)	HD (m)	MDL (km)	TDL (km)	HL (m)	RLR (−)	HI (−)	MDS (%)	Av_slope (%)	FF (−)	DD (km km^{-2})
1	Adiakor	1161	292	80	2.216	7.2280	2216	0.037	0.500	3.610	7	0.616	2.49
2	Adhilo	684	72	102	0.820	1.160	820	0.079	0.529	12.439	13	0.433	1.55
3	Adikenafiz	18340	1430	561	5.925	34.710	5925	0.083	0.558	9.468	15	0.310	2.32
4	Endazoey	973	140	120	0.899	5.980	899	0.092	0.575	13.348	11	0.827	4.28
5	Gereb Segen	5140	435	140	5.733	9.940	5733	0.026	0.414	2.442	3	0.147	2.32
6	Gereb Shegel	4180	858	462	4.405	13.040	4405	0.094	0.439	10.488	19	0.359	1.49
7	Gindae	14438	1187	455	4.700	22.170	4700	0.099	0.473	9.681	14	0.559	1.77
8	Grashitu	7890	511	189	5.564	11.090	5564	0.038	0.360	3.397	5	0.203	1.85
9	Gum Selassa	15990	2414	123	9.200	22.480	9200	0.016	0.634	1.337	3	0.403	0.93
10	Maideli	14071	1005	349	7.666	15.620	7664	0.050	0.335	4.554	8	0.202	1.52
11	Mejae	1580	256	96	2.410	4.190	2410	0.041	0.490	3.983	6	0.476	1.63

						Catchment soils			Reservoir sediment								
No	TGV (m^3)	SGV (m^3 km^{-2})	CUL (%)	SWC (%)	RD (km km^{-2})	CLAY (%)	SILT (%)	SAND (%)	CLAY (%)	SILT (%)	SAND (%)	ER_clay (−)	ER_silt (−)	LS (%)	SL (%)	DT (%)	SS (%)
1	1677	574	72	50	2.49	25	53	21	56	39	15	1.44	0.74	0	26	2	0
2	7207	10010	26	33	2.70	48	41	11	51	35	14	1.06	0.85	0	0	37	0
3	454227	31764	65	41	1.40	19	23	58	36	42	22	1.89	1.83	0	0	0	36
4	10517	7512	45	50	1.10	24	24	48	49	30	21	2.04	1.25	25	25	0	0
5	84301	19380	86	8	1.34	63	33	4	72	26	2	1.14	0.79	0	14	0	0
6	148422	17299	19	86	1.17	22	30	48	52	38	10	2.36	1.27	50	0	16	15
7	226260	19061	25	40	1.33	45	25	30	44	27	29	0.98	1.08	35	15	0	24
8	57691	11290	85	2	1.74	46	36	18	63	31	6	1.37	0.86	4	0	10	0
9	150153	6220	79	15	2.00	52	29	19	74	24	2	1.42	0.83	9	0	1	0
10	134572	13390	56	10	0.58	47	25	28	63	33	4	1.34	1.32	3	25	0	0
11	7667	2995	77	28	1.90	40	32	28	58	38	4	1.45	1.19	7	6	3	0

SY: absolute sediment yield; *A*: catchment area; HD: height difference between the outlet and the highest point in the catchment; MDL: main drainage length; TDL: total drainage length; HL: horizontal length between the outlet and the remotest point in the catchment divide; RLR: relief length ratio; HI: hypsometric integral; MDS: average main drainage slope; Av_slope: average catchment slope; FF: form factor; DD: drainage density; TGV: total gully volume; SGV: specific gully volume; CUL: fraction of catchment under cropland; SWC: fraction of catchment where soil and water conservation measures are applied; RD: density of roads and foot paths; LS: limestone; SL: shales; DT: dolerite; SS: sandstone.

Table 5
Correlation matrix between catchment properties and sediment yield

	SY	*A*	CUL	SWC	HD	MDL	TDL	RLR	HI	MDS	Av_slope	FF	DD	TGV
SSY	0.52	0.12	0.23	−0.66*	0.33	0.44	0.36	−0.06	−0.52	−0.14	−0.16	−0.62*	−0.13	0.37
SY		0.86**	0.11	−0.29	0.64*	0.82**	0.93**	−0.03	0.04	−0.2	0.02	−0.39	−0.37	0.83**
A			0.14	−0.13	0.42	0.83**	0.81**	−0.17	0.33	−0.3	−0.05	−0.24	−0.49	0.65*
CUL				−0.64*	−0.44	0.37	0.07	−0.87**	0.01	−0.83**	−0.85**	−0.32	0	−0.07
SWC					0.36	−0.46	−0.01	0.69*	0.28	0.64*	0.80**	0.52	0.23	0.11
HD						0.36	0.76**	0.59	−0.18	0.34	0.69*	−0.26	0.16	0.86**
MDL							0.68*	−0.44	−0.17	−0.59	−0.33	−0.65*	−0.54	0.52
TDL								0.13	0.19	−0.05	0.22	−0.26	−0.2	0.95**
RLR									0.11	0.94**	0.92	0.42	0.32	0.32
HI										0.26	0.10	0.59*	0.19	0.14
MDS											0.84**	0.5	0.43	0.14
Av_slope												0.24	0.08	0.42
FF													0.58	−0.29
DD														−0.16

	SGV	RD	Clay	Silt	Sand	ER_Clay	ER_Silt	LS	SL	DT	SS
SSY	0.52	−0.34	0.39	−0.33	−0.14	−0.38	0.16	−0.49	0.06	−0.15	0.12
SY	0.59*	−0.4	0.11	−0.58	0.25	−0.1	0.43	−0.13	−0.5	−0.51	0.5
A	0.31	−0.19	0.1	−0.45	0.18	0.04	0.21	0.05	−0.24	−0.39	0.3
CUL	−0.2	0.13	0.31	0.18	−0.36	−0.21	−0.21	−0.68*	−0.09	−0.48	−0.42
SWC	0.08	−0.02	−0.78**	0.03	0.64*	0.69*	0.32	0.8	−0.12	0.27	0.48
HD	0.83**	−0.57	−0.38	−0.58	0.66*	0.33	0.74**	0.39	−0.06	−0.18	0.85**
MDL	0.35	−0.4	0.38	−0.4	−0.08	−0.1	0.09	−0.18	−0.09	−0.47	0.31
TDL	0.71*	−0.37	−0.18	−0.56	0.47	0.15	0.57	0.02	−0.16	−0.5	0.72
RLR	0.43	−0.28	−0.56	−0.38	0.66*	0.39	0.55	0.61	0.13	0.24	0.63
HI	−0.13	0.42	−0.28	−0.06	0.25	0.2	0.07	0.03	−0.25	−0.03	0.21
MDS	0.29	−0.11	−0.52	−0.28	0.56	0.37	0.44	0.46	0.11	0.41	0.46
Av_slope	0.48	−0.19	−0.64*	−0.27	0.69*	0.5	0.58	0.62	−0.14	0.37	0.72*
FF	−0.45	0.21	−0.5	0.09	0.33	0.22	−0.01	0.46	0.3	−0.05	0.04
DD	−0.02	−0.21	−0.44	−0.08	0.36	0.34	0.18	0.09	0.54	−0.28	−0.02
TGV	0.86**	−0.38	−0.26	−0.58	0.56	0.21	0.71**	0.03	−0.21	−0.35	0.87**
SGV		−0.48	−0.11	−0.56	0.41	0.15	0.63*	0.02	−0.1	−0.17	0.82
RD			0.07	0.78**	−0.47	−0.34	−0.56	−0.33	−0.68	0.63	0.09
Clay				0.03	−0.85**	−0.79**	−0.59*	−0.47	0.09	−0.01	−0.54
Silt					−0.55	−0.28	−0.68*	−0.31	−0.51	0.77	−0.44
Sand						0.80**	0.87**	0.47	0.06	−0.23	0.60
ER_Clay							0.56	0.5	−0.1	−0.03	0.21
ER_Silt								0.12	0.09	−0.3	0.66*
LS									0.83**	0.05	0.25
SL										−0.52	−0.28
DT											−0.36

* Correlation is significant at 5%, ** Correlation is significant at 1%, Unless otherwise indicated with * and **, all are non-significant at 5% and 1%.

who suggested the following relationship between *A* and SSY for the Ethiopian highlands:

$$\mathrm{SSY} = 2595A^{-0.29}(r^2 = 0.59;\ n = 20) \quad (7)$$

where

SSY = specific sediment yield (t km^{-2} y^{-1}) and *A* = catchment area (km^2).

They found an inverse relationship (r^2=0.59), where 41% of the variability is yet unexplained. Eq. (7) was applied for predicting SSY to this study area using the database of this study and the model prediction was very poor (Fig. 5). The poor performance of Eq. (7) in our study area could be explained as follows: (1) in contrast to Eq. (7), *A* and SSY in this study are positively correlated (Fig. 3), (2) Eq. (7) is not explaining 41% SSY variability, hence it cannot be considered as a good model and (3) errors associated with the Ethiopian sediment yield database. Most of the sediment yield data used to develop Eq. (7) were derived from suspended sediment measurements which suffer from uncertainties in the quality of the data as reported in REDECO (2002).

Moreover, Eq. (7) does not fit the data compiled by Humphreys et al. (1997, Fig. 4) for 67 rivers. We could not find a clear relationship between catchment area and SSY despite the various attempts carried out by clustering the rivers into river basins. Overall, the relations between *A* and SSY for Ethiopian rivers, established by various researchers, are inconsistent and merit further study.

3.2.1.2. Sediment yield and other topographic characteristics. In this study, catchment area explains a major part of the variation of SY (73%; n=11) and only a very small portion of the SSY. This means that other catchment characteristics probably differ so that different sediment yields will be obtained for catchments of similar size. For example, catchment area is strongly correlated to total drainage length (TDL), main drainage length (DL) and height difference (HD) (Table 5). The correlation between TDL and SY is found to be the strongest among all other variables (r^2=0.89; n=11). It was also observed that TDL is positively correlated with specific gully volume (SGV) and HD. It is, therefore, expected that sediment yield increases with increasing drainage length as (1) the probability that the sediment reaches a water course becomes larger, (2) the TDL may take into account the contribution of gully erosion and (3) the height difference represents the potential energy available for soil erosion by runoff and for sediment transport in gullies and so influences soil erosion and sediment transport capacity indirectly. Catchment area and TDL are, however, inter-dependent and there can be an effect of multi-collinearity.

A high relief length ratio (RLR) corresponds to a more pronounced topography and thus also to a higher erosion risk. Similar observations were reported for catchments in Colorado, USA (Schumm, 1954), as

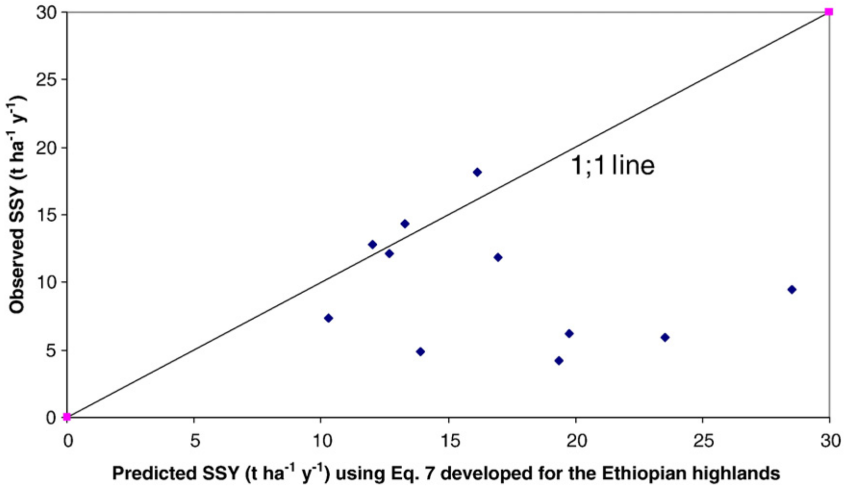


Fig. 5. Application of Eq. (7) developed for the Ethiopian highlands (Nyssen et al., 2004) to the northern Ethiopian highlands.

well as for continental-sized catchments (Summerfield and Hulton, 1994). In this study, however, the correlation is weak as the role of RLR was masked by the strong correlation between proportion of catchment area covered by soil and water conservation practices (SWC) and SSY. The area-proportion covered by cultivated land (CUL) and the RLR are inversely related.

The hypsometric integral (HI) is a catchment property that is sometimes used to explain erosion and/or sediment dynamics, even on a continental scale (Wyatt, 1993). Strahler (1964) coupled the concept of the hypsometric curve to the stage of the erosion cycle in which a catchment is situated. Catchments, which are recently incised and that have high values of the hypsometric integral (HI), are in the early phase of the erosion cycle and are characterized by high erosion values. During the later stages, a catchment evolves to lower dynamic equilibrium values of HI, whereby, the average slope decreases and the fraction of wide valley bottoms increases, resulting in lower values of sediment yield. In this study, however, the HI is not varying significantly between catchments, which means that all catchments are in the same stage of incision.

SSY is negatively correlated to drainage density (DD), but positively correlated with specific gully volume (SGV), though both are not significant. On the other hand, DD is poorly correlated to SGV. The weak correlation between SSY and DD, while there existing a stronger positive correlation between SSY and SGV, might indicate that gullies are more important as sediment source rather than serving as sediment transport pathway in the study area. The sediment transport pathway in this study area is strongly controlled by the positive correlation between sediment yield and HD. Therefore, in this study area, it can be concluded that a high drainage density does not necessarily reflect a high gully erosion rate. This shows that, if the gullies are stable, their role in explaining sediment yield variability is limited.

According to Suresh (2002), the spatial variability of SSY among catchments can also be controlled by a form factor (FF), an index for the shape of the catchment. An inverse correlation exists between SSY and FF unlike the common assumptions that FF and the drainage flow hydrograph/sedigraph and peak flow rates should be positively related. The latter assumes that as compactness increases, the transporting time for sediment and flow will decrease and as a result there will be higher peak flows and higher sediment yields. In this study, however, the inverse relationship is due to the strong positive correlation between main drainage length (LD) and A. This shows that sediment transport connectivity is controlled more by other actors like HD. Furthermore, in the studied catchments, there exists a positive correlation between the slope of the main drainage line (MDL) and the FF. This means that the reducing effect on SSY of the less compact catchments and longer travel distances is counteracted by steeper slope gradients.

3.2.2. Sediment yield and human activities

There exists an inverse significant correlation between the fraction of the catchment area where soil and water conservation practices are applied (SWC) and SSY (r=−0.66) (Table 5). This finding is in agreement with similar studies carried out in the study area. For instance, Gebremichael et al. (2005) found that the implementation of stone bunds in cropland reduces soil loss by sheet and rill erosion approximately to one third of that on plots with no physical structures. Semi-quantitative modeling on the effects of SWC practices by Haregeweyn et al. (2005) shows that the impact of SWC in reducing sediment yield is significant.

On the other hand, SWC and average catchment slope (Av_slope) are strongly correlated (r=0.80), which indicates that SWC practices are mainly implemented on the steeper slopes. This strong correlation has masked the role of Av_slope in influencing the sediment yield variability. As a result, sediment yield and average slope are poorly correlated. SWC and CUL are inversely correlated (r=−0.64), as well as Av_slope and CUL (r=−0.85). This explains that in steeper catchments, cultivated land is limited and consequently the implementation of SWC practices increases. Cultivated land, for instance, is dominant in less steep catchments like Gereb Segen, Grashitu and Gum Selassa (Table 4). The relation between SWC, Av_slope and CUL is clearer in the case of Gereb Shegel catchment which is characterized by the steepest Av_slope (19%) and the least CUL (19%) but the most wide-spread SWC (86%) practices. Consequently, these characteristics resulted in low sediment yield from the catchment. The inverse correlation between SWC and CUL is due to the lower adoption rate of SWC practices in cultivated lands by the local farmers. Naudts (2002) assessed the perception of the farmers towards the impact of stone bunds in the study region and, besides a generally positive perception, found two most important perceived disadvantages of stone bund construction in cultivated land i.e. (1) they would attract rats and (2) the stone bunds occupy too much space within their field plots. Therefore, many farmers are reluctant to apply SWC practices in their cultivated fields.

Footpaths are widely present in all catchments while vehicle roads are limited to few catchments. Road/footpath density (RD) was expected to be positively correlated with SY and/or SSY. However, the correlation between RD and sediment yield in this study area is poor. The road effect can be explained in terms of sediment transport connectivity as well as a source of sediment when gullies develop in road banks (Sidle et al., 2006). The sediment transport connectivity in these study catchments

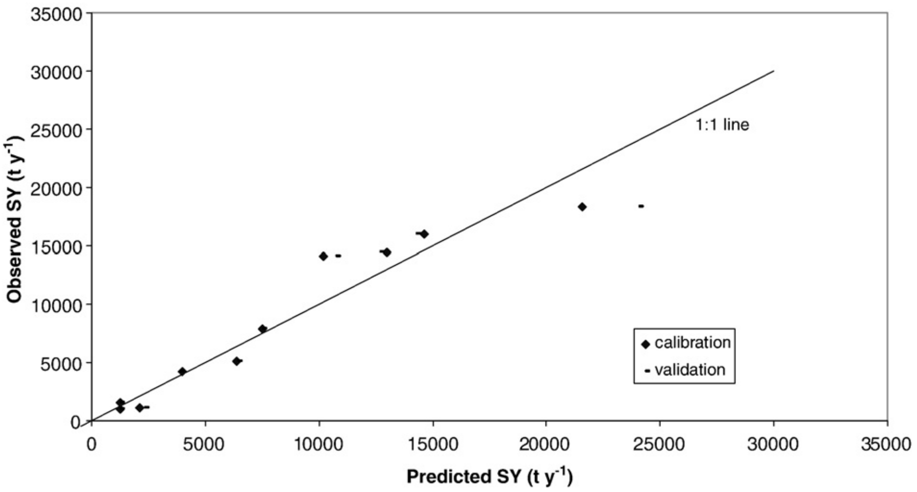


Fig. 6. Predicted versus observed SY at calibration and validation for 11 catchments in Tigray.

was strongly controlled by a combined effect of high HD and a generally steep average catchment slope. The poor correlation between RD (i.e. foot paths) and sediment yield, on the other hand, indicates that the role of footpaths is not pronounced in altering the soil surface, which is unlike that of the major vehicle roads (Sidle et al., 2006).

3.2.3. Sediment yield and soils/geology

One would expect that both SY and SSY could increase with an increase of the finer soil fraction in the catchments. In this case, however, soil texture does not have a significant role in explaining sediment yield variability. This is due to a low variability of soil texture across the catchments. Classification of the average clay, silt and sand fractions using the USDA Soil Textural Classification System yielded a soil texture within clay category for most catchments (Table 1). Similarly, geology was found to be less important in controlling sediment yield variability as there was no large contrast between catchments.

3.3. Multiple regression models

Since one single catchment property alone cannot explain a large part of the observed variation in sediment yield, multiple regression models were constructed. Two models for SY and SSY with two variables for each model were developed (Eqs. (8) and (9)). SWC and Av_slope were selected during the step-wise regression model analysis for obtaining the best SY and SSY models, respectively, as they exhibited a high partial correlation. Similarly, important variables during the bi-variate analysis like A in SY and FF in SSY models were not included in the respective multiple regression model as they have lower partial correlation.

SY model:

$$\mathrm{SY} = 690\ \mathrm{TDL} - 0.58\ \mathrm{SWC}\ \left(R^2 = 0.96;\ n = 11\right) \quad (8)$$

P	0.0001	0.017
R_p^2	0.96	0.49

SSY model:

$$\mathrm{SSY} = 0.86\ \mathrm{Av\_slope} - 0.269\ \mathrm{SWC} + 10\ \left(R^2 = 0.80; n = 11\right) \quad (9)$$

P	0.005	0.000	0.0001
R_p^2	0.66	0.79	

where

SY = absolute sediment yield (t y^{-1}), SSY = specific sediment yield (t ha^{-1} y^{-1}), TDL = total drainage length (km), Av_slope = average catchment slope (%), SWC = fraction of catchment area treated with soil water conservation practices (%), R^2 = coefficient of determination of the multiple regression models, R^2_p = partial R^2 and P = P-value of parameter estimate.

Figs. 6 and 7 show the predicted versus observed sediment yield for SY and SSY, respectively. The models gave quite reasonable estimate of sediment yield, under limited number of explanatory variables, with MEs of 0.88 and 0.66 and RRMSEs of 30% and 24% at validation for SY and SSY, respectively. The SY model (Eq. (8)) is more robust so that it can be used in this and similar study areas, with a high degree of accuracy, for planning purposes like estimation of annual sedimentation rates

In the case of the SSY model (Eq. (9)), 20% of the variability is yet unexplained. The variation in observed SSY that cannot be explained by the model might be attributed to the following reasons: (1) there are errors in measured sediment yield, which are estimated to be in the order of 40% to 50% in the case of small retention ponds (Verstraeten and Poesen, 2002); (2) not all of the influencing properties are known and studied; (3) a spatial distribution of influencing properties is not incorporated; (4) no attention is paid to small anthropogenic landscape elements like earth banks, hedges, furrows, parcel borders or tillage direction, which can have a significant impact on sediment production and delivery as shown by Van Oost et al. (2000).

Walling (1983) stressed the limitations of a spatially and temporally lumped parameter, which fails to reproduce the distributed and time-

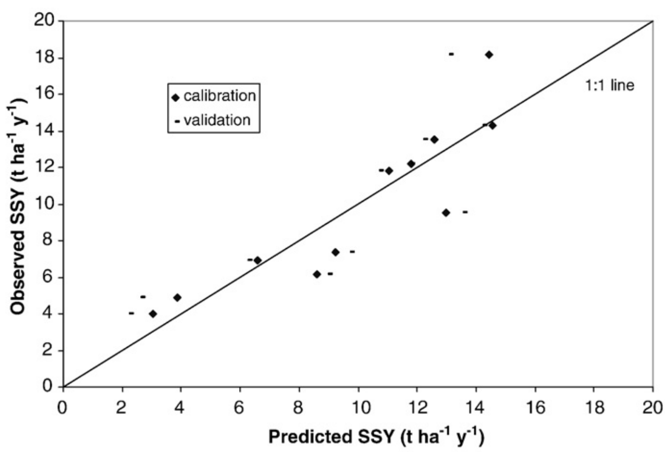


Fig. 7. Predicted versus observed SSY at calibration and validation for 11 catchments in Tigray.

varying nature of erosion and sediment transport. This inherently limits their application to practical problems such as the evaluation of the impacts of different land management strategies on sediment delivery (Van Rompaey et al., 2001). Spatially-distributed erosion and sediment delivery models are needed to overcome these problems. However, extended datasets on sediment yield are necessary to calibrate and validate these models.

4. Conclusions

There is a high spatial variation in SSY between the 11 studied northern Ethiopian catchments with an average SSY value of 9.89 (S.D.±4.46) t ha^{-1} y^{-1}. The sediment yield in this study area is high compared to world standards. Knowledge of sediment yield from small catchments (10–10 000 ha) is very important in order to understand the linkage between soil erosion processes on hill slopes and sediment transport in large rivers.

The bi-variate correlation for the eleven catchments showed that total drainage length (TDL), catchment area (A), height difference (HD), in this order of importance, significantly affect absolute SY positively. TDL is also strongly correlated with HD and also with specific gully volume (SGV). Therefore, the strong positive correlation between TDL and absolute SY might be attributed to: (1) the low sediment deposition rate due to high sediment transport connectivity, increased erosive power and less infiltration of runoff as a result of increased HD and (2) increased SGV at the scale of this study.

Interactions between controlling factors is important. Area-proportion of catchment area treated with soil and water conservation practices (SWC) is strongly correlated with average catchment slope (Av_slope) ($r=0.80$) and with area-proportion occupied by cultivated land (CUL) ($r=-0.64$). CUL in turn is strongly correlated with Av_slope ($r=-0.81$). These inter-relationships show that in steeper catchments, the proportion of cultivated lands decreases and consequently the implementation of SWC activities increases. SWC activities are less adopted where there are relatively high proportion of cultivated lands and less steep slopes.

Multiple regression models for the prediction of SY (Eq. (8))) and SSY (Eq. (9)) were developed for the study area. Absolute sediment yield (SY) can be predicted by measuring only two parameters with a high ME of 0.88. Therefore, this model can be applied for predicting SY when planning new reservoirs in the northern Ethiopian highlands. The prediction of SSY shows a reasonable accuracy with a ME of 0.66 although the accuracy is less than that of the SY model. The less predictive potential of the SSY model can be attributed to the higher variability of SSY between the study catchments. This high variability can be explained by the variability of the controlling factors between catchments. However, no attention was paid to small anthropogenic landscape elements like earth banks, hedges, furrows, parcel borders or tillage direction, which can have a significant impact on sediment production and delivery.

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