Available online at www.sciencedirect.com

SCIENCE DIRECT®

Geomorphology 69 (2005) 315–331

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Specific sediment yield in Tigray-Northern Ethiopia: Assessment and semi-quantitative modelling

Nigussie Haregeweyn[a,b], Jean Poesen[b,*], Jan Nyssen[a,c], Gert Verstraeten[b], Joris de Vente[b], Gerard Govers[b], Seppe Deckers[c], Jan Moeyersons[d]

[a] *Department of Land Resources Management and Environmental Protection, Mekelle University, P.O. Box 231, Mekelle, Ethiopia*
[b] *Physical and Regional Geography Research Group, K.U. Leuven, Redingenstraat 16, B-3000 Leuven, Belgium*
[c] *Institute of Land and Water Management, K.U. Leuven, Vital Decosterstraat 102, B-3000 Leuven, Belgium*
[d] *Agriculture and Forestry Economics, Royal Museum for Central Africa, B-3080 Tervuren, Belgium*

Received 20 May 2004; received in revised form 10 February 2005; accepted 10 February 2005
Available online 7 April 2005

Abstract

Sediment deposition in reservoirs is a serious off-site consequence of soil erosion in Tigray (Northern Ethiopia). So far insufficient and less reliable sediment yield data have been collected for Northern Ethiopia. Nor are there any adaptable methodologies for sediment yield assessment in the country as a whole, which could be used when designing new reservoirs. This study addresses those problems by (1) undertaking reservoir sediment deposition measurements and (2) by calibrating and adapting the Pacific Southwest Inter Agency Committee (PSIAC) and the Factorial Scoring Model (FSM) sediment yield assessment models to Ethiopian conditions. Field rating of catchment characteristics and the sediment yield data from the reservoir survey were used for calibration and validation of the models. Our reservoir survey indicates that specific sediment yield (SSY) varies significantly between catchments: i.e. 487 t km^{-2} $year^{-1}$ to 1817 t km^{-2} $year^{-1}$ with an average of 1054 (± 446) t km^{-2} $year^{-1}$. Since the variability of SSY is high between the studied reservoirs, care should be taken in the study area to adopt representative SSY values during reservoir and soil water conservation planning. The PSIAC SSY prediction is found to fit well with observed SSY without adjustment. While the FSM was found to have, after modifying the description of factors and incorporating new controlling factors, a good fit between the predicted and observed SSY. Studies of the relationship between the known sediment yield rates and the catchment conditions using semi-quantitative approaches such as PSIAC and FSM can be of substantial benefit in extrapolating data for areas where no detailed information is available in a cheap and quick way. However, calibration and modification of such models may be necessary if they are to be used beyond the region where they were developed.

Keywords: Catchment; Northern Ethiopia; Reservoir survey; Sedimentation; Specific sediment yield; PSIAC and FSM models

---

* Corresponding author. Tel.: +32 16326425; fax: +32 16326400.
E-mail address: Jean.Poesen@geo.kuleuven.ac.be (J. Poesen).

0169-555X/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2005.02.001

1. Introduction

Rainfall is seasonal and erratic in Northern Ethiopia, particularly in Tigray. As a result, there is strong seasonal (about 8 months) moisture stress limiting the productivity of the rainfed agriculture in the region (Bard et al., 2000; ILRI-CGIR, 2004). Realising the problem, the construction of dams for irrigation has been a priority for the Government of Ethiopia for the last decade. In Tigray alone, 55 dams were built from 1994 to 2002 to store runoff in reservoirs (Fig. 1).

However, the construction of the dams did not proceed as planned (SAERT, 1994) because of different practical challenges. Siltation of these reservoirs is a serious off-site consequence of soil erosion as it threatens the sustainability of the reservoirs.

So far, insufficient and less reliable sediment yield data have been collected/compiled systematically for the region. Such data are, however, crucial when designing new reservoirs. Nor are there any adaptable methodologies for sediment yield assessment in the country as a whole. In some cases, estimation of sediment yield has been based on use of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965). However, this model was not designed for soil loss estimation at catchment level (Hudson, 1995). In other cases, a range of specific sediment yield (SSY) values between 800 and 1200 t km^{-2} year^{-1} has been adopted across the region, but no exact source is provided.

Therefore, as both reliable data and prediction methods are lacking, different designers follow different approaches to take account of loss of storage due to sedimentation. This means that the risk of siltation

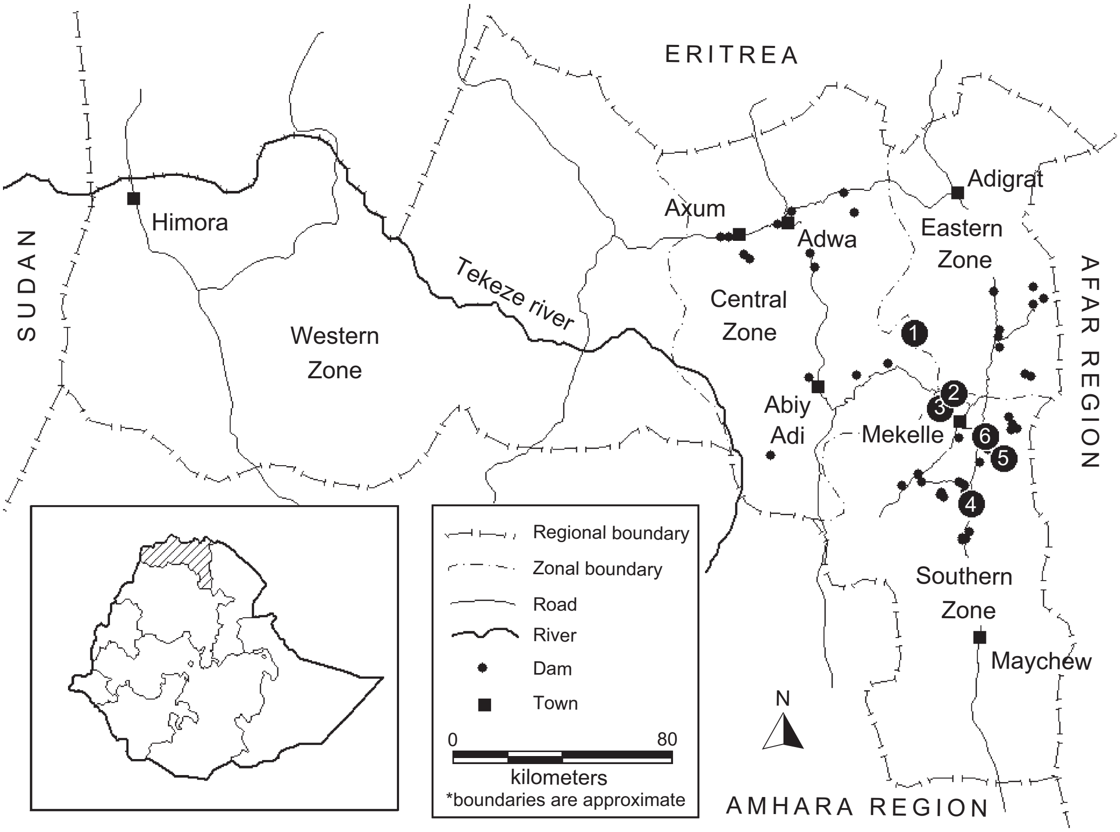

Fig. 1. Location of visited reservoirs (with dots) a dot with the following numbers represents the reservoirs studied in detail: i.e. 1 Gindae, 2 Gereb Shegel, 4 (Gereb Segen, Grashitu, Mejae, Maideli, Gum Selasa), 6 Adihilo.

is usually poorly addressed at the planning stage of the reservoirs. Hence, sediment yield data and appropriate prediction tools are essential requirements for planning and managing water resource development schemes in the country.

Therefore, the objectives of this study were (1) to assess the extent of specific sediment yield (SSY) variability in Tigray, (2) to evaluate to what extent semi-quantitative tools can predict accurately the SSY and (3) to identify the major factors controlling the SSY based on the information provided by objective 2.

2. Materials and methods

2.1. Study area

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). The region has a total area of 50 078 km^2 (out of which 19% is suitable for cultivation) and a population of more than 3.8 million (CSA, 2001).

The climate is generally 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 of the rainfall occurs in 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 west 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, 2004) and are seriously affected by land degradation due to their long cultivation history (starting 3000 BC, Hurni, 1989; Bard et al., 2000), steep topography and erosive rains. In contrast, the lowlands are sparsely populated and have soils that are less eroded and exploited (TFAP, 1996).

2.2. Survey of sediment deposition

2.2.1. Site selection and data collection

A detailed investigation of deposited sediment was made in 8 representative reservoirs located within a radius of 70 km from Mekelle, Tigray's regional capital (Fig. 1). Availability of reports detailing the planning stage (head work, catchment and history of the dam), and the absence of other reservoirs within the catchment (non-cascading dams) were also used as criteria during the selection. All the reservoirs were surveyed when they were dry during the period April to June 2003, which was an exceptionally dry year.

The selected reservoirs had been created by constructing earth embankments to harvest seasonal runoff. The stored runoff could then be used later in the season for supplementing the rain (when dry spells occur) and/or for full irrigation during the dry part of the year (SAERT, 1994). There are several basic components of each dam body: the dam; the intake canal for supplying irrigation water to the irrigable area, which is fixed at some height above the riverbed so as to give storage allowance for the expected sedimentation and the spillway (Fig. 2). The major features of the surveyed reservoirs are shown in Table 1.

2.2.2. Assessment of specific sediment yield

Here, the term specific sediment yield (SSY) refers to the mass of sediment per unit area of a catchment that enters the reservoir. SSY in the 8 studied reservoirs was calculated with the following relationship:

$$\mathrm{SSY} = 100{*}M/(A{*}\mathrm{STE}{*}Y) \quad \text{(Verstraeten and Poesen, 2001)} \tag{1}$$

where, SSY = specific sediment yield (t km^{-2} year^{-1}), M = sediment mass (t), A = catchment area (km^2), STE = sediment trap efficiency (%), Y = age of the reservoir (years), and

$$M = \mathrm{Sv}{*}dBD \tag{2}$$

Sv = the measured sediment volume in the reservoir (m^3), dBD = the area-weighed average dry bulk density of the sediment (t m^{-3}).

Sediment thickness was measured by observing sediment profiles (up to 3 m deep) in pits along transects, with 15 to 39 pits per reservoir depending on the size and nature of the original bottom surface of the reservoir (see examples in Fig. 3). 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.

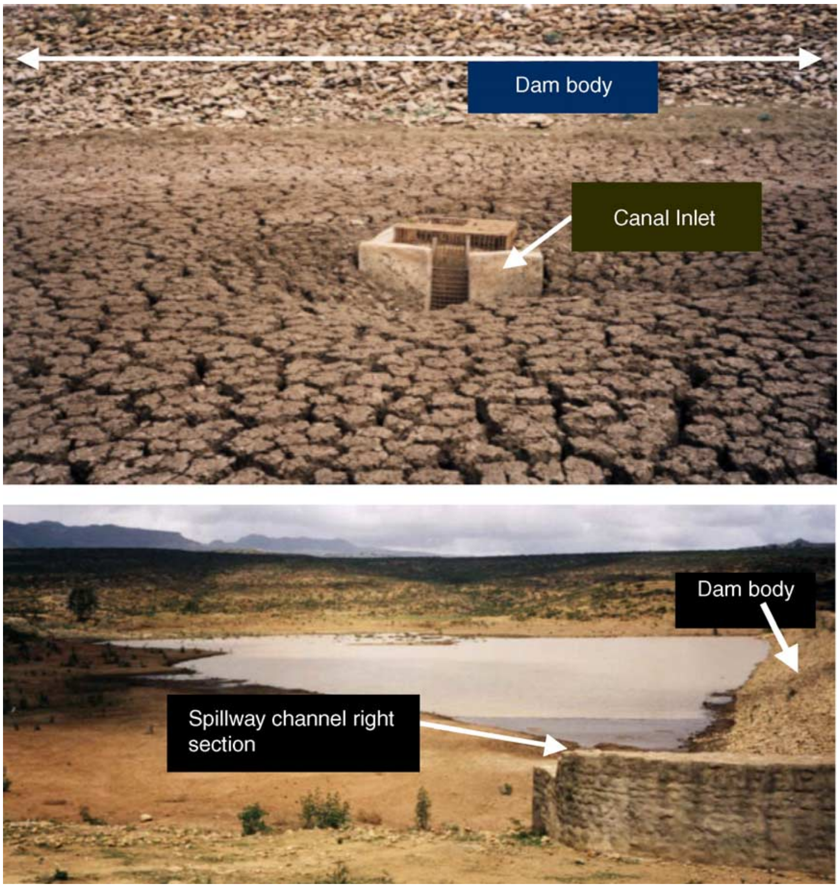

Fig. 2. Typical dam structures in Grashitu (upper) and Gindae (lower).

The trapping efficiency of the reservoirs was assessed based on one season field monitoring (summer 2003) and interviewing the local farmers about the history of the reservoir. All reservoirs are less than 7 years old and spillage has never occurred for most of the reservoirs since their construction.

Table 1
Characteristics of the studied reservoirs

Reservoir	DA (km^2)[a,b]	Dam location, UTM (Zone P37)[b]		Elevation at the dam (m)[b]	US (10^3 m^3)[c]	DS (10^3 m^3)[c]	LE (year)[c]	Reservoir area when full (ha)[c]	Dam height (m)[c]	CL (m)[c]
		X	Y							
Grashitu	5.11	555 102	1 460 677	2084	170	18	20	6.72	9	477
Gereb Segen	4.35	553 619	1 465 412	2100	340	22	25	11.70	14.9	208
Gereb Shegel	8.58	548 945	1 502 177	1921	1000	200	NA	17.10	20	378
Gum Selassa	24.14	558 642	1 463 566	2146	1900	476	30	48.00	13.5	428
Gindae	11.87	536 297	1 522 368	1979	790	142	20	13.50	19.5	483
Adihilo	0.72	561 327	1 486 172	2308	110	4	9	2.50	11.4	177
Maideli	10.05	556 547	1 461 226	2130	1580	270	27	38.60	15.00	486
Mejae	2.56	555 021	1 458 530	2135	300	13	40	6.00	13.5	266

DA: drainage area, US: useful storage, DS: dead storage, LE: life expectancy, CL: crest length, NA: not available.

[a] Determined by GPS readings.

[b] This study.

[c] Various reports of SAERT—see extensive list in De Wit (2003).

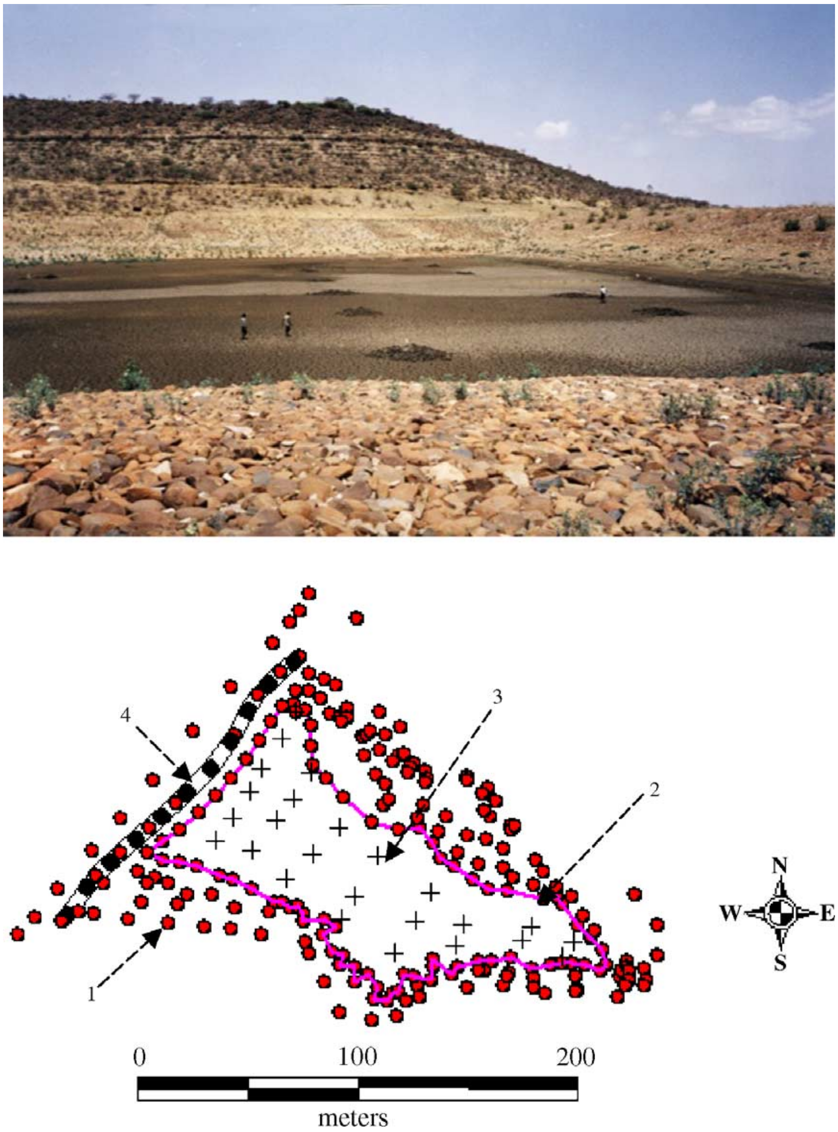

Fig. 3. Part of the layout of the 26 profile pits at Gereb Shegel reservoir where sediment deposits are up to 3 m deep near the dam (upper) and details of topographic mapping and pit layout in Adihilo reservoir (lower): (1) theodolite readings, (2) sediment boundary, (3) profile pits and (4) dam.

Dry bulk density (dBD) was determined by the gravimetric method. Undisturbed representative sediment samples were taken using core rings (volume 1×10^{-4} m^3) from 8 to 12 sampling sites per reservoir (near the dam axis, in the middle, side and at the inlet of the reservoir), and at a minimum of two different depths in the profile pit. The profile dBD analysis result from pits indicates that dBD varies spatially both within the reservoir and vertically in the profile. For instance, in the case of Gereb Shegel, 9 pits were sampled and it was found that dBD varies between 1.35 t m^{-3} at the inlet and 0.97 t m^{-3} near the dam. For the same number of pits ($n=9$), analysis of vertical variation of dBD was made by analyzing dBD values from cores taken in two regions at two depths (upper and lower) in a profile pit. There exists some variation of dBD between the upper and lower zones, i.e. 1.05 t m^{-3} and 1.16 t m^{-3}, respectively. A similar trend exists in other reservoirs. In this study, the vertical variability of dBD was considered by taking average dBD values obtained from different depths in a profile while the horizontal variation was accounted by producing a dBD map using Thiessen polygons in IDRISI® with point dBD values obtained from all pits in the reservoirs. The map produced by Thiessen Interpolation produced the expected distribution of dBD both along and across the reservoir. A map of the mass of accumulated sediment per unit area was then produced by multiplying the sediment DEM and dBD map layers. Then the total mass of the sediment accumulated over the years was determined by using the 'EXTRACT' module in IDRSI. More details of the reservoir survey approaches can be found in Nigussie et al. (submitted for publication).

In general, associated errors during sediment volume and sediment yield determination are low: (1) sufficient precision was obtained both during sediment surface mapping, sediment thickness measurement (with precision of 1 cm) and during sampling for dBD analysis and during DEM generation (1 m by 1 m), and (2) the effect of STE determination in the overall error is very low as most of reservoirs have never spilled since construction.

2.3. Modelling specific sediment yield

2.3.1. Modelling concepts

A wide variety of sediment yield models exist, ranging from semi-quantitative empirical models that predict relative long term average sediment yield to dynamic physically based models capable of predicting within event variations of absolute sediment output.

Since semi-quantitative empirical models are simple and fast to apply and require a limited amount of input data, we selected two existing semi-quantitative models for application to our data: the Pacific Southwest Interagency Committee (PSIAC) model (PSIAC, 1968) and the Factorial Scoring Model (FSM) (Verstraeten et al., 2003).

2.3.2. Description of semi-quantitative models

2.3.2.1. Factorial Scoring Model (FSM). A power relationship between SSY and catchment area was established for 60 catchments in Spain and the catchment area only explained 17% of the observed variability in SSY (Avendano Salas et al., 1997). Since this relationship alone cannot be a valid tool for predicting sediment deposition rates for planned reservoirs, Verstraeten et al. (2003) developed a Factorial Scoring Model (FSM) to better explain the spatial variability of SSY in Spain. The model is based on a power relationship between catchment area (A) and the specific sediment yield and a scoring index (I). The index is calculated by multiplying the ratings for five factors (topography, gullies, vegetation cover, lithology and catchment shape) as I=T.G.V.L.S (based on the description given in Table 2).

Table 2
Description of the scores for factors used to calculate the scoring index I in Eq. (3) (after Verstraeten et al. (2003))

Factor	Score	Description
Topography (T)	1	Very gentle slopes near reservoir and main rivers; elevation differences <200 m within 5 km
	2	Moderate slopes near reservoir and main rivers, elevation difference between 200 and 500 m within 5 km
	3	Very steep slopes near reservoir; elevation difference >500 m within 5 km
Gullies (G)	1	Bank and ephemeral gullies are rare
	2	A few bank and/or ephemeral gullies can be observed
	3	Many bank and/or ephemeral gullies an be observed
Vegetation cover (V)	1	Contact cover of the soil is very good >75% of the soil is protected)
	2	Moderate contact cover (25–75% of the soil is protected)
	3	Little contact cover (<25% of the soil surface is covered)
Lithology (L)	1	Dominant limestone, sandstone (low weathering degree)
	2	Dominant neogene sedimentary deposit (gravels, etc.)
	3	Strongly weathered (loose) material and/marls
Catchment shape (S)	1	Elongated catchment shape with one main river channel draining to the reservoir
	2	Catchment shape in between elongated shape and (semi-circular catchment shape)
	3	(semi) circular catchment shape with many rivers and draining into the reservoir and/or with much direct runoff from hill-slopes to the reservoir

Finally the variables were related as follows:

$$\mathrm{SSY} = 4136A^{-0.43} + 4.55I + 211 \quad (\text{Verstraeten et al., } 2003) \tag{3}$$

where, SSY is area specific sediment yield t km^{-2} year^{-1}, A is catchment area in km^2, I=T.G.V.L.S (see Table 2 for description of factors and scores).

Eq. (3) was found to explain well the variation of SSY in Spain (r^2 of 85%, ME of 0.83 and RRMSE of 33%) (Verstraeten et al., 2003). The index itself explained 66% of the variation in SSY. However, the model was not validated for different data sets.

2.3.2.2. *Pacific Southwest Interagency Committee Model.*

The Pacific Southwest Interagency Committee (PSIAC, 1968) developed a catchment inventory method for use in the Western United States to predict the order of magnitude of specific sediment yield based on nine physical factors and associated scoring. The factors with their range values are presented in Table 3. There are five rating classes for which only the description of the three sediment yield levels (high, moderate and low) is provided. The intermediate ranges, i.e. moderate to high and low to moderate sediment yield values can be interpolated within that range as required. Each factor except topography is paired with another factor that has a similar influence on sediment yield. The pairings are surface geology and soil, climate and runoff, ground cover and land use, and upland and channel erosion. Each factor is rated separately, but the ones paired are usually considered concurrently, and the degree of interdependence of the two is reflected in the similarity of assigned values. Finally, the sum of these scores is then converted into an estimate of mean annual specific sediment yield (Table 3). The PSIAC factors were rated in a more quantitative way to predict sediment yield from sagebrush rangelands by Johnson and Gebhardt (1982). This approach would reduce subjectivity during rating as compared to original PSIAC approach. However, it requires the availability of a large quantitative data set especially related to climate, runoff, groundcover and soils which is not available in either of our study catchments. Since there is lack of quantitative data and since the objective of this study is to develop rapid assessment

Table 3
PSIAC (1968) factors used to characterize catchment condition and assess SSY (developed for Southwest USA)

Factor	Score	Main characteristics
Surface geology	0	(a) Massive hard formations
	5	(a) Rocks of medium hardness, (b) moderately weathered, (c) moderately fractured
	10	(a) Marine shales and related mudstones and siltstone
Soils	0	(a) High percentage rock fragments, (b) aggregated clays, (c) high in organic matter
	5	(a) Medium texture, (b) occasional rock fragments, (c) caliche layers
	10	(a) Fine texture, easily dispersed, saline–alkaline, high shrink–swell characteristics, (b) single grain silts and fine sands
Climate	0	(a) Humid climate with rainfall of low intensity, (b) precipitation in form of snow, (c) arid climate with low intensity storms, (d) arid climate with rare convective storms
	5	(a) Storms of moderate duration and intensity, (b) infrequent convective storms
	10	(a) Storms of several days duration with short periods of intense rainfall, (b) frequent intense convective storms, (c) freeze–thaw occurrence
Runoff	0	(a) Low peak flows, (b) low volume of runoff per unit area, (c) rare runoff events
	5	(a) Moderate peak flows, (b) moderate volume of flow per unit area
	10	(a) High peak flows, (b) large volume of flow per unit area
Topography	0	(a) Gentle upland slopes (<5%), (b) extensive alluvial plains
	10	(a) Moderate upland slopes (<20%), (b) moderate floodplain development
	20	(a) Steep upland slopes (>30%), high relief, little or no floodplain development
Ground cover	−10	(a) Completely protected by vegetation, rock fragments, litter. Little opportunity for rainfall to reach erodible material
	0	(a) Cover <40%; noticeable litter, (b) if trees present understory not well developed
	10	(a) Ground cover <20%, vegetation sparse, little or no litter, (b) no rock in surface soil
Land use	−10	(a) No cultivation, (b) no recent logging, (c) low intensity grazing
	0	(a) <25% cultivated, (b) 50% or less recently logged, (c) <50% intensively grazed, (d) ordinary road and other construction
	10	(a) >50% cultivated, (b) almost all of the area intensively grazed, (c) all of area recently burned
Upland erosion	0	(a) No apparent signs of erosion
	10	(a) About 25% of the area characterised by rill and gully or landslide erosion, (b) wind erosion with deposition in stream channels

(continued on next page)

Table 3 (*continued*)

Factor	Score	Main characteristics
Upland erosion	25	(a) >50% of the area characterised by rill and gully or landslide erosion
Channel erosion and sediment transport	0	(a) Wide shallow channels with flat gradients, short flow duration, (b) channels in massive rock, large boulders or well vegetated, (c) artificially controlled channels
	10	(a) Moderate flow depths medium flow duration with occasionally eroding banks or bed
	25	(a) Eroding banks continuously or at frequent intervals with large depths and long flow duration, (b) active headcuts and degradation in tributary channels

After summation of the individual scores the total Index class can be determined and translated into an estimated sediment yield and rating class.	Total score (Pt)	Estimated sediment yield ranges ($t\ ha^{-1}\ year^{-1}$)	Rating class
	>100	>18.3	1 (high)
	75–100	6.1–18.3	2
	50–75	3.0–6.1	3 (moderate)
	25–50	1.2–3.0	4
	0–25	<1.2	5 (low)

tools that are less data demanding, we applied the original PSIAC (1968) model.

2.3.3. Data collection

The approach used for data collection for both PSIAC and FSM scores was similar, except for the quantitative analysis of the catchment area relationship in the case of FSM. Catchment area was obtained by digitising the watershed divide lines from topographic maps (1:50 000 scale map) with point ground verification using Global Positioning System (GPS). Scores for each FSM and PSIAC factor was obtained as follows. First, topographic maps (1:50 000) and climate (rainfall records) were inspected in the office. Secondly, a field campaign was undertaken in each catchment by a team of 3 scientists and 3 Bachelor thesis students, with different backgrounds (hydrology, geology, geomorphology soil erosion and soil conservation). The team made transects through each catchment during which the specific features of the catchment were characterized. After a complete overview of the catchment was obtained, each factor was evaluated. First each expert produced his own scores independently for each factor followed by a group discussion after which a single value reflecting the view of the majority of experts was assigned.

It was not possible to use the original description of factors of the FSM scoring (Table 2) for Ethiopian catchments, except for catchment shape. Therefore, we modified the scoring table in order to adapt it to Ethiopian conditions (compare Tables 2 and 5). (1) In general, the Ethiopian catchment topography is relatively steep. Therefore a rating ‘1’ is assigned for average slope less than 6%, rating ‘2’ for intermediate slopes between 6 and 15% and a rating of ‘3’ for slopes steeper than 15%. (2) In the study area, ephemeral gullies are rare so that the evaluation was based on the density of active permanent bank gullies as well as the connectivity between them as described in Table 5. (3) Vegetation cover in the study areas is generally sparse and there is a significant variation in cover between seasons, since in most catchments agricultural land use is dominant. At the start of the rainy season (mid-June to third week of July), the soil surface is bare and ploughed; as a result the soil surface is poorly protected. While for the rest of the season (end of July to mid of September), there is good cover. However, in most of the catchments there is a significant stone cover, as high as 60% that has the same protective effect as vegetation cover. (4) The catchments vary in lithology from high percentage of exposed bedrock rated as ‘1’ to strongly weathered materials such as colluvium and marl rated as ‘3’.

In addition, the SSY data derived from sediment deposition measurements in the reservoirs of each respective catchment were used for the model calibration and evaluation.

2.3.4. Model analysis

2.3.4.1. Model calibration. For the evaluation of PSIAC, the scores of all factors were summed to estimate the yield rating and rating class based on Table 3. A regression model was fitted between the observed SSY and the score total (Pt) for 8 catchments. For the FSM, model evaluation (i.e. based on Eq. (3)) and modelling of new factors were undertaken to fit it to Northern Ethiopian condition. Comparisons were made between the observed and predicted SSY to assess the calibrated model performance.

2.3.4.2. Model validation. In both models, the calibrated models were validated for all the catchments by applying the $n-1$ approach since there were a limited number of catchments i.e. fitting eight different models excluding one catchment at a time and predicting SSY for that excluded catchment. Finally, the model accuracy was evaluated by comparing observed and predicted SSY.

2.3.4.3. Evaluation of the 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)

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n} (Q_i - P_i)^2}{\sum_{i=1}^{n} (Q_i - Q_{\mathrm{mean}})^2} \tag{4}$$

where, ME is Model Efficiency, n is number of observations, Q_{mean} is the mean observed value, Q_i the observed value, P_i the predicted value.

The value of ME can range from $-\infty$ 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):

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

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. Measured specific sediment yields

There is high spatial variation in SSY between catchments: i.e. 487 t km^{-2} year^{-1} to 1817 t km^{-2} year^{-1} with average of 1054 (± 487) t km^{-2} year^{-1} (Table 4). Within our study area, Hunting (1976) monitored the suspended sediment yield for the Bellet (115 km^2) and Maidello (153 km^2) catchments and found 1700 t km^{-2} year^{-1} and 3300 t km^{-2} year^{-1}, respectively, in which 10% of the total SSY is estimated to be bed load. These values are high when compared to the values found in this study. Several factors may explain this difference.

Table 4
Assessment of sediment volume, sediment mass and specific sediment yield

No.	Reservoirs	TV (m^3)	dBD (t m^{-3})	TM (t)	Age (year)	DA (km^2)	TE (%)	SSY (m^3 km^{-2} year^{-1})	SSY (t km^{-2} year^{-1})
1	Grashitu	36340	1.14	39451	5	5.11	85	1673	1817
2	Gereb Segen	12357	1.23	15421	3	4.35	100	947	1182
3	Gereb Shegel	19114	1.11	20902	5	8.58	100	446	487
4	Gum Selassa	110679	1.00	111932	7	24.14	90	728	736
5	Gindae	56460	1.27	72190	5	11.87	100	951	1216
6	Adihilo	2452	1.38	3420	5	0.72	100	681	950
7	Maideli	66695	1.08	70357	5	10.05	98	1354	1429
8	Mejae	5581	1.42	7900	5	2.56	100	436	617
	Average		1.21					902	1054
	S.D.		0.15					432	446

TV: total volume; dBD: dry bulk density; TM: total mass; DA: drainage area; TE: trap efficiency; SSY: specific sediment yield.

The measurements by Hunting only cover a single wet season following the driest year on record. Furthermore, soil conservation measures were implemented on a large scale between 1978 and 2003, thereby possibly reducing sediment yields. Finally, sediment load may increase with catchment size as channel erosion becomes dominant (e.g. Church et al., 1999).

3.2. Semi-quantitative modelling in sediment yield assessment

3.2.1. FSM and its controlling factors

3.2.1.1. Model building. First Eq. (3), which was calibrated for Spanish catchments by Verstraeten et al. (2003), was applied to predict SSY variability in Tigray's catchments. The predictions correlated very poorly with observed sediment yields. This can be attributed to the empirical nature of the model and it confirms that the conditions in Spain were significantly different from the conditions in our study area.

An attempt was therefore made to see if a modified FSM would perform better. First, it was noted that the relationship between catchment area and SSY is not significant ($r^2=0.01$). This could reflect (1) the size of the catchments and the limited range (0.7–24 km^2), (2) that in the study catchments, gully erosion is dominant and the connectivity between gullies is very high and (3) that there are other sensitive variables (e.g. geology, cover and others) that control SSY, as discussed in Section 3.2.2.

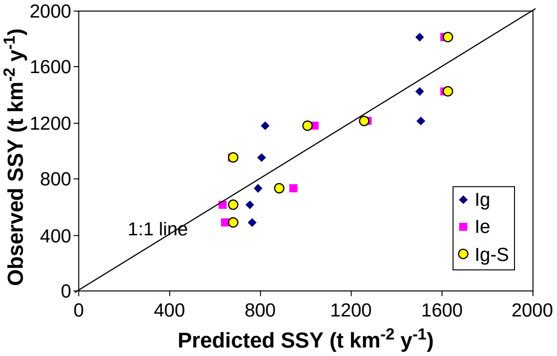

Fig. 4. Scatter plot between observed and predicted SSY using different scoring indices (Ig, Ig-S and Ie) for Northern Ethiopian catchments (calibration).

Table 5
Description of the scores for factors used with semi-quantitative analysis of SSY in Northern Ethiopian catchments (after modifying Verstraeten et al., 2003)

Factor	Score	Description
Topography[a]	1	Gentle slopes near the reservoir and main rivers; elevation differences <300 m within 5 km.
	2	Moderate slopes near the reservoir and main rivers; elevation difference between 300 and 750 m within 5 km.
	3	Very steep slopes near reservoir; elevation difference >750 m within 5 km.
Gullies (*G*)[a]	1	Gullies are rare or channel banks and beds have low erodibility (or stabilized) and poor connectivity between gullies.
	2	A few active gullies with medium connectivity.
	3	Many active gullies with lots of bank collapse and high connectivity.
Surface cover (*V*)[a]	1	Vegetation and/or stone cover of the soil is very good (>75% of the soil is protected).
	2	Moderate vegetation and/or stone cover (25–75% of the soil is protected).
	3	Little contact cover (<25% of the soil surface is protected).
Lithology (*L*)[a]	1	High percentage of rock outcrops.
	2	Coarse colluvium (e.g. gravels).
	3	Strongly weathered (loose) material and marls.
Catchment shape (*S*)[b]	1	Elongated catchment shape with one main channel draining to the reservoir.
	2	Catchment shape in between elongated shape and semi-circular catchment shape.
	3	Semi circular catchment shape with many rivers draining into the reservoir and/or with much direct runoff from hill slopes to the reservoir.
Conservation practice (*P*)[c]	1	High density of soil conservation structures (>70% of the contributing area has been treated).
	2	Medium density (30% to 70%) of conservation structures.
	3	Low density (<30% of the contributing area).
Climate (*C*)[c]	1	Arid climate with low annual rainfall (Fournier index <75).
	2	Semi-arid climate with storms of moderate duration and intensity, (Fournier index between 75 and 150).
	3	Wet climate with relatively high annual rainfall, concentrated in a few months (Fournier index >150).

[a] Modified factors.
[b] Factors removed.
[c] Newly incorporated factors.

Since catchment area is not a good controlling parameter for explaining SSY variability in the studied catchments, we were not able to maintain the same model structure as described in Spain (see Eq. (3)). Hence we analysed the SSY variability using the scoring index for the five factors (Ig) only (Table 6). The index alone explained fairly well the SSY variability ($r^2=0.68$; Eq. (6), Table 7) with ME = 0.69 and RRMSE = 61% (Fig. 4).

$$\mathrm{SSY} = 5Ig + 627 \quad \left(r^2 = 0.69\right) \tag{6}$$

where, SSY specific sediment yield in t km^{-2} year^{-1}, Ig = T. G.V.L.S (see Tables 5 and 6 for description of factors and scorings).

The contribution of the original controlling factors was assessed by evaluating average SSY at the three scoring levels in 8 catchments (Table 7). The presence of gullies is found to be the primary explanatory factor for high SSY variability followed by cover, lithology, topography and catchment shape which is non-significant.

Hence, we excluded catchment shape and created a new index (Ig_S) i.e. the product of the remaining four factors (Table 6). As a consequence, the relationship between index (Ig_S) and observed SSY was highly improved ($r^2=0.82$) (Eq. (7), Table 7), with ME = 0.82 and RRMSE of 38% (Fig. 4).

$$\mathrm{SSY} = 14\mathrm{Ig\_S} + 514 \quad \left(r^2 = 0.82\right) \tag{7}$$

where, SSY as described in Eq. (6), Ig_S = T.G.V.L (see Tables 5 and 6 for description of factors and scorings).

Table 7
Evaluation of FSM factors and scoring index models in explaining the SSY variability in Northern Ethiopian catchments

Scores	Average SSY(t km^{-2} year^{-1}) for FSM factors at different scoring levels						
	T	*G*	*V*	*L*	*S*	*C*	*P*
1	736	617	nr	719	959	nr	552
2	900	873	818	nr	1088	1054	950
3	1180	1300	1291	1166	1083	nr	1276
Max–Min	444	683	474	448	124	0	724

nr: no rating

Parameters	Scoring index		
	Ig	Ig_S	I_e
r^2	0.68	0.82	0.84
Calibration		(Fig. 4)	
ME	0.69	0.82	0.84
RRMSE	61	38	46
Validation			(Fig. 5)
ME			0.68
RRMSE			22

T: topography; *G*: presence of gullies; *V*: surface cover; *L*: lithology; *S*: catchment shape; *C*: climate; *P*: conservation factors; Ig = T.G.V.L.S; Ig_S = T.G.V.L; I_e = T.G.V.L.P; SSY: specific sediment yield (measured).

3.2.1.2. Modelling new factors

Climate. The Fournier (1962) climatic index was used to analyze the erosivity of climate as one factor.

$$C = p^2/P \quad (\text{Fournier, } 1962) \tag{8}$$

where, *C* is Fournier index, *p* is mean monthly precipitation of the wettest month (mm), *P* is mean annual precipitation (mm).

Table 6
Scoring of studied catchments for FSM factors described in Table 5

No.	Catchments/reservoirs	Factor scores and indexes						Ig	Ig_S	I_e	Observed SSY (t km^{-2} year^{-1})
		T	*G*	*V*	*L*	*S*	*P*				
1	Grashitu	3	3	3	3	2	3	162	81	243	1817
2	Gereb Segen	2	2	3	3	1	3	36	36	108	1182
3	Gereb Shegel	3	2	2	1	2	1	24	12	12	487
4	Gum Selassa	1	3	3	3	1	3	27	27	81	736
5	Gindae	3	3	2	3	3	3	162	54	162	1216
6	Adihilo	3	2	2	1	3	2	36	12	24	950
7	Maideli	3	3	3	3	2	3	162	81	243	1429
8	Mejae	2	1	2	3	2	1	24	12	12	617

T: topography; *G*: presence of gullies; *V*: surface cover; *L*: lithology; *S*: catchment shape; *P*: conservation factors; Ig = T.G.V.L.S; Ig_S = T.G.V.L; I_e = T.G.V.L.P; SSY: specific sediment yield (measured).
(1), (2), (3): low, moderate, high contribution to erosion rate and sediment delivery is expected.

Application of the model helped us to group the Tigray region into the following climate erosivity classes: '1' is related to *C* value <75 for arid areas such as Agushella (southwest lowlands), '2' C value between 75 and 150 for semi-arid areas in central, northern and eastern region of Tigray and '3' for C value >150 for areas with relatively high total rainfall, concentrated from July to September especially in southern and western parts of the region. However, in our case there is no variability of SSY that could be explained by climate (Table 7), because the studied catchments are all located in C class '2'. The variable could be a significant controlling factor if a countrywide analysis was undertaken and this merits further study.

Conservation practices. Over the last decade, there has been widespread implementation of soil and water conservation practices in most catchments. This includes mainly physical structures like stone bunds in all land use types, trenches in pasture and shrub lands and check dams in the gullies. Since all the catchments are located in a semi-arid environment, the structures are designed to conserve both the soil and runoff. Hence, if there is sufficient spatial coverage with such physical structures in each catchment, the expected sediment yield could be significantly reduced. Research by Desta et al. (in press) in the study area indicate that the implementation of stone bunds in cropland reduces soil loss by sheet and rill erosion ca. to one third of that on the plots with no physical structures. Hence, a new factor " conservation practice (*P*)" was incorporated to our FSM (Table 5) and incorporating this index 'I_e' (Table 6) has improved the model, i.e. $r^2=0.84$ (Eq. (9), Table 7) with ME=0.84 and RRMSE=46%) (Fig. 4). Although catchment area is not included in this model, its efficiency is of the same order of magnitude as calibrated in Spain (ME=0.83 and RRMSE=33%, Verstraeten et al., 2003). The calibration helped to identify the local controlling factors and finally provided an adoptable model. Conservation practice factor is found to be the major controlling factor for SSY variability in the study area (Table 7).

Since the model (Eq. (9)) incorporates the most important factors controlling SSY in the region, and since the calibration prediction accuracy is better, we validated it for each catchment, and the model is able to explain about 69% of the variation of SSY with ME=0.68 and RRMSE=22% (Table 7, Fig. 5)

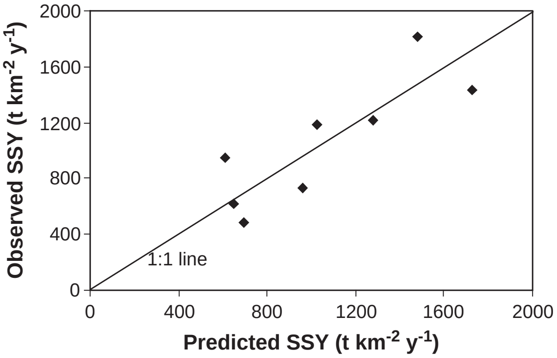

Fig. 5. Scatter plot between observed and predicted SSY for FSM model using index Ie for Northern Ethiopian catchments (validation).

$$SSY = 4I_e + 588 \quad (r^2 = 0.84) \tag{9}$$

where, SSY as described in Eq. (6), I_e=T.V.G.L.P (see Tables 5 and 6 for description of factors and scorings).

3.2.2. Application of the PSIAC model to assess SSY variability

The nine PSIAC factors were rated based on the descriptions given in Table 3 for Northern Ethiopian catchments. The sum of the values for the appropriate characteristics of the nine factors yielded the total score (Pt) and rating class for the catchments (Table 8).

A linear regression was fitted between Pt and the observed SSY value (Eq. (10) and Fig. 6).

$$SSY = 0.27Pt - 9 \quad (r^2 = 0.87) \tag{10}$$

where, SSY is specific sediment yield (t ha^{-1} year^{-1}), Pt is PSIAC total score obtained by summing each individual factor (Table 8).

The validation result also confirms that the prediction is quite good (ME=0.76 and RRMSE=63%) (Fig. 7).

The scores obtained are of a similar order of magnitude to those reported for the Southwest US: PSIAC scores are normally converted to a range of possible sediment yields (Tables 3 and 8). Fig. 8 shows our data points together with the lower limiting score and lower limiting SSY for each class in Southwest US. As can be seen in the figure, the

Table 8
Scores and correlations of various PSIAC factors and correlations with observed SSY in the Northern Ethiopian catchments

PSIAC factors	Catchments								r^2
	Grashitu	Gerb Segen	Gereb Shegel	Gum Selassa	Gindae	Adihilo	Maideli	Mejae	
Geology	10	0	3	0	10	3	5	5	0.33
Soil	7	7	3	8	6	3	7	6	0.20
Climate	7	7	7	7	7	7	7	7	ns
Runoff	7	7	8	6	8	8	8	5	0.10
Topography	10	10	18	6	18	20	10	6	ns
Surface cover	5	5	0	5	0	0	5	2	0.25
Land use	10	10	5	10	5	3	10	10	0.10
Upland erosion	15	15	8	15	20	8	15	10	0.35
Channel erosion and Sediment transport	25	20	5	10	5	5	20	5	0.65
Total score (Pt)	96	81	57	67	79	57	87	56	0.87
Rating class	2	2	3	3	2	3	2	3	
Observed SSY (t ha^{-1} year^{-1})	18.2	11.8	4.9	7.4	12.2	9.5	14.3	6.2	

ns: non-significant, r^2 : coefficient of determination between observed SSY and score of each factor.

overall agreement is good and moreover it indicates that most of our catchments are located within the high SSY rating range (i.e. SSY > 6.1 t ha^{-1} year^{-1}). The SSY values are high when compared to the soil formation rates in the region, which vary between 2 and 5 t ha^{-1} year^{-1} (Hurni, 1983) and emphasize that appropriate soil and water conservation measures should be implemented to control both the on-site and off-site impacts of erosion.

To assess the contribution of the nine PSIAC factors in explaining the variation of SSY between the catchments in Tigray, linear regression and correlation analysis between observed SSY and the score of each factor was undertaken across the catchments (Table 8). These relationships are discussed below.

The effect of surface geology is important ($r^2 = 0.33$), because there are large contrasts in erodibility of geological formations in the catchments. These include highly weathered materials like marl, shale and alluvial and colluvial deposits (e.g. Grashitu, Gindae). Other catchments have a more resistant geology such as dolerite (e.g. Gereb Shegel and Adhihilo).

Soil is also an important variable in explaining SSY variability across the catchments ($r^2 = 0.20$). In the studied catchments, the effect of soil ranges from

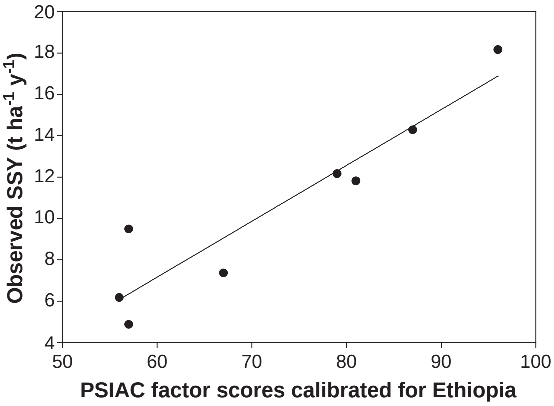

Fig. 6. Relation between PSIAC scores (Pt) and observed SSY for Northern Ethiopian catchments.

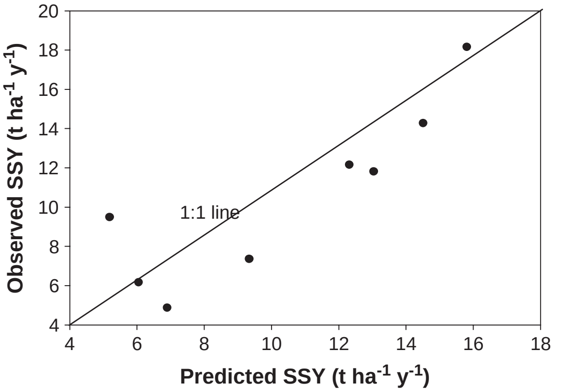

Fig. 7. Scatter plot between PSIAC predicted and observed SSY for Northern Ethiopian catchments.

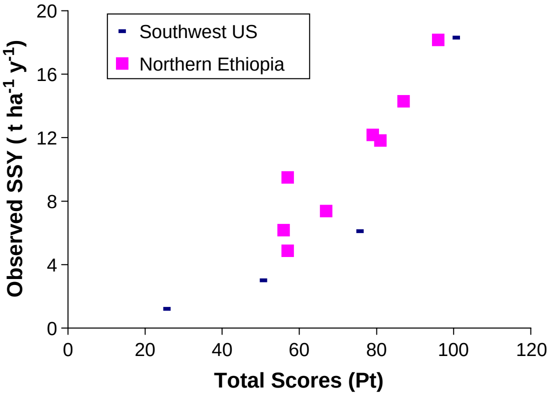

Fig. 8. Evaluation of the PSIAC model for Southwest USA and Northern Ethiopian catchments.

low-moderate in areas where there is high to low stone cover (Adihilo, Gereb Shegel) to moderate-high in areas where there is a soil that is characterized between medium to single grained textured (less aggregated) soils. The erodibility of a soil is influenced by stone cover (e.g. Poesen et al., 1994; Nyssen et al., 2001) and grain size (e.g. Morgan, 1986; Evans, 1980).

Climate is not important for explaining variability in SSY, the variability of climate between catchments is low; hence rainfall does not have any impact on the variation of SSY. There is some variation in runoff conditions ($r^2=0.10$) between catchments with high to moderate runoff generation, as runoff generation is also affected by other factors (land use, soil and water conservation practices, slope, lithology and soil conditions) (USDA-SCS, 1964).

Topography is also weakly correlated with SSY; although three catchments are characterized by steep upland slopes (slope>30%) and three others by moderate slopes (less than 20%). The lack of a clear influence of topography is shown by the Grashitu and Gereb Segen catchments, which have the highest sediment yield but only moderate slopes. The effect of topography may be partly masked by interaction effects. Because stoniness may be expected to increase with slope gradient, the effects of slope steepness and soil cover on erosion may counteract each other.

The ground cover is well correlated with SSY ($r^2=0.25$). The impact on SSY variability is strong as some catchments remain tilled and bare for the first part of the rainy season (June to half July). While others are significantly protected due to the presence of a high stone cover as high as 60% (e.g. Gereb Shegel, Adihilo).

The effect of ground cover in reducing soil erosion has been demonstrated by different cover experi-

Fig. 9. Gully headcut in the Grashitu catchment.

ments: e. g. cover related to interception and cover in direct contact with the soil surface such as the effect of crop residues (Morgan, 1986) and stones (Van Asch, 1980; Poesen et al., 1994; Nyssen et al., 2001). In addition to interception, ground cover dissipates the energy of surface runoff by increasing roughness (Morgan, 1986).

Land use shows only a moderate influence on the variability of specific sediment yield ($r^2=0.10$), mainly because there is no major variation of land use across the catchments; more than 50% of the area of most catchments is cropland.

Upland erosion is closely related to SSY ($r^2=0.35$). In our study catchments, erosion occurs by rill, inter-rill and gully and channel bank erosion. The catchments where the dominant land use is agriculture where the soil is highly erodible have moderate to high rill and inter-rill erosion rates (e.g. Grashitu, Gum Selassa, Gereb Segen). Erosion rates are lower for catchments where shrub land is dominant and stone cover is high (e.g. Gereb Shegel, Adihilo).

Not surprisingly, channel erosion is the dominant variable explaining SSY ($r^2=0.65$). Channels are potential sediment sources from banks, beds and active gully head cuts (see Figs. 9 and 10). There is high connectivity between the drainage lines as well. The high sediment production from channels is mainly because of the presence of very erodible parent materials like marl in the case of Grashitu and due to the vertic character of clay formations (Nyssen et al., 2000) that are susceptible to piping that ends with bank collapse and active head cuts (e.g. Gereb Segen, Maideli). Hence, priority should be given to rehabilitating the channels and the channeled sub catchments when planning soil and water conservation activities in the catchments.

Table 9
Evaluation of PSIAC and FS modeling approaches

Criteria	PSIAC	FSM
Factors	Greater number of factors (9) but inter-related (e.g. land use and cover)	Lower number of factors (5) but less inter-related
	Relative importance between factors is well assessed (e.g. channel erosion versus topography)	Does not differentiate the relative importance between factors
Scoring	Wider scoring range (−10 to 25) and possibility to interpolate scores (1–5) that could experience more subjectivity	Smaller scoring range and no possibility to interpolate hence low subjectivity
	Requires experienced and multidisciplinary approach	Relatively easy to understand and apply the scoring
Calibration of new factors	Difficult as score range is wide (five) and the score varies between factors	More easy as there are only three values and the scores for each factor are the same

3.3. Evaluation of the PSIAC and Semi-Factorial Modeling approaches

From a review of the two modeling approaches and based on our experience during modeling, an evaluation of PSIAC and FSM was made as summarized in Table 9.

Fig. 10. Lateral channel bank retreat and head cutting in the Maideli catchment.

4. Summary and conclusion

This study first assessed the spatial variability of SSY in eight reservoirs/catchments by measuring the volume and mass of deposited sediment in the reservoirs and also by characterizing the reservoirs and their respective catchments. The sources of errors during SSY analysis (e.g. bulk density, trap efficiency) were fully considered during investigation. The survey shows that SSY varies significantly between catchments, i.e. from 487 t km^{-2} $year^{-1}$ to 1817 t km^{-2} $year^{-1}$ with an average of 1054 (± 446) t km^{-2} $year^{-1}$. The high spatial variability in SSY is mainly associated with differences in lithology, ground cover, extent of bank gullies and human activities. However, reservoir designers in the study area still have been adopting the same range of SSY values (800 to 1200 t km^{-2} $year^{-1}$) throughout the region irrespective of this high spatial variability of SSY between catchments. This approach leads to risky or uneconomical design of reservoirs. Hence, it is recommended that the local conditions controlling sediment yield should be considered during the planning stage of reservoirs.

The PSIAC (1968) and the FSM models were evaluated using the study catchments. In both cases, the approach to data collection and data analysis was similar: a field campaign by a team with different professional backgrounds was undertaken in each catchment in order to score each model's factors. The accuracy of both models was evaluated by comparing the observed versus the predicted SSY using ME and RRMSE tests. The PSIAC method was found to fit the observed data well, with no major adjustments made for the original PSIAC model. In the case of FSM, a three-stage calibration was undertaken and the model was adapted for the study area by incorporating new controlling factors. When validated, this model provided good predictions. From an analysis of the relative roles of the various factors in controlling SSY based on the two models, the important role of the presence of a gully network was emphasized.

Studies of the relationship between known sediment yield (SSY) and the catchment characteristics involving semi-quantitative approaches such as PSIAC and FSM could be of substantial benefit in extrapolating data to areas without information in a cheap and quick way. However, it should be kept in mind that such models must be calibrated first if they are to be used beyond the region where they were developed. Moreover, involving experienced and related experts during rating of the individual scores can minimize the subjectivity of the scoring.

Acknowledgements

We thank VLIR and Mekelle University for the financial support of this study as part of the Zala Daget Collaboration Project “Success and failures of soil conservation and dam construction in Tigray highlands, Northern Ethiopia”. We thank also Fassil Kebede, SAERT staffs and Woreda authorities and farmers in the study area for facilitating our work during office and field works. Finally, we would like to thank Des Walling and John Boyle for providing valuable comments on the earlier version of this paper.

References

Avendano Salas, C., Sanz Montero, E., Rayan, C., Gomez Montana, J.L., 1997. Sediment yield at Spanish reservoirs and its relationship with drainage area. Proc. of the 19th Symposium of Large Dams, Florence. ICOLD (International Committee on Large Dams), Paris, pp. 863–874.

Bard, K., Coltorti, M., Diblasi, M.C., Dramis, F., Fattovich, R., 2000. The environmental history of Tigray (Northern Ethiopia) in the middle and late Holocene: a preliminary outline. African Archaeological Review, 17 (2), 65–68.

Church, M., Ham, D., Hassan, M., Slaymaker, O., 1999. Fluvial clastic sediment yield in Canada: scaled analysis. Canadian Journal of Earth Sciences, 36, 1267–1280.

CSA (Central Statistics Authority), 2001. Statistical Abstract 2000. Federal Democratic Republic of Ethiopia, Central Statistical Authority. March 2001, Addis Ababa, Ethiopia, p. 403.

Desta Gebremichael, Nyssen, J., Poesen, J., Deckers, J., Mitiku Haile, Govers, G., Moeyersons, J., in press. Effectiveness of stone bunds on controlling soil erosion on cropland in the Tigray highlands, Northern Ethiopia. Soil Use and Management.

De Wit, J., 2003. Stuwmeren in Tigray (Noord-Ethiopie): Kenmerken, sedimentatie en sedimentbronnen. MSc thesis, Katholieke Universiteit Leuven, Faculteit Wetenschappen, Department Geografie-geologie.

Evans, R., 1980. Mechanics of water erosion and their spatial and temporal controls: an empirical viewpoint. In: Kirkby, M.J., Morgan, R.P.C. (Eds.), Soil Erosion. Wiley, Chichester, pp. 109–128.

FAO., 2004. http://www.fao.org/giews/english/basedocs/eth/ethpop1e.stm.

Fournier, F., 1962. Map of erosion danger in Africa south of Sahara. Explanatory note. EEC, Commission for Technical Cooperation in Africa.

Hudson, N., 1995. Soil Conservation, third ed. Batsford, London (391 pp.).

Hunting, T.S., 1976. Tigray Rural Development Study, Annex 2: Water Resources. Hunting Technical Services Limited, Hemel Hempstead, Great Britain. 211 pp.

Hurni, H., 1983. Soil formation rates in Ethiopia, Addis Ababa, FAO/ Ministry of Agriculture. Joint Project EHRS, Working paper No. 2.

Hurni, H., 1989. Late Quaternary of Simen and other mountains in Ethiopia. In: Mahaney, W. (Ed.), Quaternary and Environmental Research on East African Mountains. Balkema, Rotterdam, pp. 105–120.

ILRI-CGIR, 2004. Causes of and responses to land degradation www.ilri.cgiar.org/InfoServ/Webpub/Fulldocs/WorkP25/Causes.htm.

Johnson, C.W., Gebhardt, K.A., 1982. Predicting sediment yields from Sagebrush rangelands. Proc of the Workshop on Estimating Erosion and Sediment Yield on Rangelands, Tucson, Arizona March 7–9, 1981. USDA-ARS, Agricultural Reviews and Manuals, vol. 26. ARM-W, pp. 145–156.

Morgan, R.P.C., 1986. Soil Erosion and Conservation. Longman Scientific and Technical, Wiley, New York.

Nash, J.E., Sutcliff, J.V., 1970. River flow forecasting through conceptual models. Part I: a discussion of principles. Hydrology, 10, 282–290.

Nigussie Haregeweyn, Poesen, J., Nyssen, J., De Wit, J., Mitiku Haile, Govers, G., Deckers, S., submitted for publication. Reservoirs in Tigray: characteristics and sediment deposition problems. Land Degradation and Development.

Nyssen, J., Moeyersons, J., Deckers, J., Mitiku Haile, Poesen, J., 2000. Vertic movements and the development of stone covers and gullies, Tigray highlands, Ethiopia. Zeitschrift für Geomorphologie, N.F., 44, 145–164.

Nyssen, J., Mitiku Haile, Moeyersons, J., Poesen, J., Deckers, J., 2001. Removal of rock fragments and its effect on soil loss and crop yield. Soil Use and Management, 17, 179–187.

Poesen, J., Torri, D., Bunte, K., 1994. Effects of rock fragments on soil erosion by water at different spatial scales: a review. Catena, 23, 141–166.

PSIAC, 1968. Factors affecting sediment yield and selection and evaluation of measures for the reduction of erosion and sediment yield. Pacific Southwest Inter-Agency Committee (PSIAC) report of the water management subcommittee, 27 pp.

SAERT., 1994. Sustainable agriculture and environmental rehabilitation in Tigray, basic text working document, Mekelle, Ethiopia.

TFAP (Tigray Forest Action Program)., 1996. Tigray Bureau of Agriculture and Natural Resources Development, Regional Government of Tigray, Mekelle Ethiopia, 122 pp., unpublished.

USDA-SCS, 1964. Hydrology. Section 4 part I, Catchment planning. National Engineering Handbook. US Department of Agriculture, Soil Conservation Service, Washington, DC.

Van Asch, Th.W.J., 1980. Water erosion on slopes and land sliding in a Mediterranean landscape. Utrechtse Geografische Studies (20 pp.).

Van Rompaey, A.J.J., Verstaeten, G., Van Oost, K., Govers, G., Poesen, J., 2001. Modeling mean annual sediment yield using a distributed approach. Earth Surface Processes and Landforms, 26, 1221–1236.

Verstraeten, G., Poesen, J., 2001. Variability of dry sediment bulk density between and within retention ponds and its impact on the calculation of sediment yield. Earth Surface Processes and Landforms, 26, 375–394.

Verstraeten, G., Poesen, J., de Vente, J., Konincks, X., 2003. Sediment yield variability in Spain: a quantitative and semiqualitative analysis using reservoir sedimentation rates. Geomorphology, 1246, 327–348.

Virgo, K.J., Munro, R.N., 1978. Soil and erosion features of the central plateaux of Tigray, Ethiopia. Geoderma, 20, 131–157.

Wischmeier, W.H., Smith, D.D., 1965. Predicting rainfall erosion losses from cropland east of the Rocky Mountains. Agriculture Handbook, vol. 282. U.S. Department of Agriculture, Washington, DC. 47 pp.